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BETTER GYPSUM BOARD AT LOWER COST

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The views and conclusions expressed and the recommendations made in this report are entirely those of the authors and should not be construed as expressing the opinions of Alberta Municipal Affairs.

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FOREWORD

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EXECUTIVE SUMMARY

Introduction

This study examined the feasibility of using fly ash as a partial replacement for gypsum in wallboard.

Fly ash is a by-product of coal combustion in thermal power plants. It is produced in large quantities in Alberta and, with the exception of a small amount currently used in the construction industry, must be otherwise disposed of at significant cost.

On the other hand, the cost of mining, transportation and processing of raw gypsum is escalating and quantities are diminishing. However, while presently manufactured gypsum board contains 91 percent pure gypsum by weight, Canadian Standards Association (CSA) standards currently only require wallboard to contain 65 percent gypsum, providing room within the current standard for decreasing the gypsum concentration.

Research at the University of Calgary over the past decade suggested that Alberta fly ash had properties which might render it especially suitable to partially replace the gypsum in wallboard. This study set out to further test that possibility.

Objectives

The study had the following objectives:

1. To analyze and assess the suitability of fly ash for incorporation into residential building products with respect to health and safety considerations.

2. To formulate wallboard with various concentrations of fly ash as a replacement for gypsum.

3. To test the wallboard and assess the performance of the various fly ash mixes with a view to evaluating optimum quantities of fly ash as a replacement for gypsum.

4. To compare the performance of the fly ash gypsum board with conventional gypsum board.

5. To perform such tests as recommended by the CSA to further assess the suitability of the product in terms of compliance with applicable standards.

6. To evaluate the economic aspects of adoption of fly ash gypsum board for industry and consumers.

7. To assess energy and natural resource consequences of a potential switch to fly ash gypsum board production.

Approach

The research commenced with a review of the literature focussed on the properties of fly ash, the effect of combining fly ash with gypsum and the suitability of the material for use in residential building products.

A number of formulations of 0, 10, 20, 30 and 40 percent fly ash gypsum mixes were prepared using three different types of fly ash. Tests were conducted on consistency, setting time, temperature-time relationships of the slurry, density, compressive strength and rate of water absorption.

CSA standards and testing requirements were then identified and samples were formulated and tested to assess potential compliance. Costs and benefits to industry and consumers were then assessed.

Results

Results varied somewhat depending on the type of fly ash used. However, analysis and test results indicated:

- Fly ash is suitable for incorporation in gypsum residential building products.
- Replacement of up to 30% of the gypsum in wallboard with fly ash is feasible.
- Manufacturing characteristics were not substantially affected.
- Fly ash/gypsum wallboard samples on average exceeded pure gypsum samples tested for breaking strength.
- Fly ash/gypsum wallboard showed superior resistance to the affects of moisture and temperature in humidified deflection testing.
- Fly ash/gypsum specimens tested gave very high core hardness value compared to pure gypsum samples.
- All samples tested, including the pure gypsum, exceeded CSA nailhead pull resistance maximum values.
- Fly ash/gypsum samples evidenced a 9 to 10% reduction in mass per unit area or average weight.
- Samples containing fly ash gave lower thermal conductivity readings than those with pure gypsum, suggesting superior insulation properties.
- Cost savings could be achieved in fly ash/gypsum wallboard production.
- Gypsum resources could be significantly extended through incorporating fly ash in wallboard.

In other words, the report found that a lighter stronger board with superior moisture, impact and thermal resistance could be produced at lower cost, extending gypsum resources and providing a recycling opportunity for an otherwise largely waste product by incorporating fly ash in gypsum board at up to 30% by weight. The product would meet or exceed most current CSA standards.

1.0 INTRODUCTION

1.1 Background

Fly ash is a by-product of the combustion of pulverized coal in thermal power plants. It is removed by mechanical collection, electrostatic precipitation and fabric filters as a fine particulate residue from the combustion gases before they are discharged into the atmosphere.

Alberta fly ash production accounts for more than 60 to 70 percent of the total ash production in Canada. About 2 million tonnes of fly ash and bottom ash (another by-product) is produced in Alberta every year. Research at the University of Calgary over the last decade has proven that Alberta fly ashes possess self hardening and pozzolanic properties.[1] (ie. reacts with calcium hydroxide in the presence of water to form cementitious materials as explained in greater detail in Section 2.0). These properties help in utilization of fly ashes in concrete as a partial replacement of cement. Research results also suggest that Alberta fly ashes can be used to replace 80 to 90% Portland Cement in concrete for pavement construction. Many innovative uses for fly ash have been developed in different countries over the years. The categories listed below represent areas of utilization with the highest potential for providing a long term outlet for fly ash and bottom ash.

Landfill and Cover Material
Water and Soil Improvement
Roadways and Pavements
Drainage
Structural Products
Lightweight Aggregate
Grout and Mortar and
Metal Extraction

Nonetheless, only about 10% to 15% of the total ash produced in Alberta, or for that matter anywhere else, is used for construction or

other purposes. The rest has to be disposed at a cost to the utilities and therefore, the consumer. Many of the uses of fly ash are directly related to its pozzolanic property. Use of ash as a pozzolan has historically represented the largest outlet for fly ash but uses for other purposes identified above account for significant amounts of ash as natural resources continue to decrease in supply or availability. This study investigates the use of fly ash as partial replacement of gypsum in wallboard.

Gypsum is the name of the mineral which is chemically a dihydrate of calcium sulphate ($CaSO_4 \cdot 2H_2O$). The name is derived from the Greek word "Gypsos", meaning chalk.[2] The use of gypsum as a building material is well recorded. The Ancient Egyptians are known to have used gypsum for plaster and mortar in the construction of pyramids. In India gypsum has been used for mortar in desert areas for many centuries.

Major producers of gypsum are Canada, France, Iran, the U.S.A. and the Soviet Union.

Recently, the cost of gypsum has increased considerably.

Gypsum wallboards meeting CSA Standards are supposed to contain no less than 65% gypsum. Presently manufactured, 12 mm thick gypsum wallboard contains about 7.92 kg of core material per square metre. This core material contains about 0.097 kg/m^2 of dry additives such as starch, potash and paper fibre. The purity of gypsum is about 92%. Therefore, the core material contains about 91% pure gypsum by weight.

Partial replacement of gypsum by fly ash should be feasible and should reduce the cost of wallboard significantly. Alberta fly ashes are lightweight materials and are highly pozzolanic. The wallboards containing Alberta ashes are likely to be more durable and economical as well as lighter in weight.

The production of gypsum and manufactured gypsum products are closely associated with the building construction industry. The increase in construction that follows economic prosperity is always reflected in increased demand for gypsum products. About 307,000,000 square metres of gypsum wallboards were manufactured at 13 different locations throughout Canada in 1988 alone,[3] and some production occurs in Alberta. The building construction industry has been generating continued high demand for gypsum board.

Since there is a limit in the exploitation of natural resources, there will always be the threat of diminishing quantities, be it gypsum or any other resource. Energy requirements and costs also increase for mining and processing of gypsum and other cementitious materials with decreasing the supply of natural resources. On the other hand, there is a considerable stockpile of waste materials which may be used effectively in the construction industry. Fly ash is one such material produced in large amounts as a result of major expansion in coal-fired generating stations in Canada, as well as throughout the world. The partial replacement of cement by fly ash in Portland Cement concrete has been widely accepted and constitutes a major use of the ash. It is also widely used in highway sub-base construction and reclamation of land.

The depletion of oil and gas as an energy source and also the environmental and political problems associated with nuclear energy on a large scale point to a rapidly increasing use of coal in the coming years. As more and more utilities begin to use coal for fuel, the amount of waste products such as fly ash and bottom ash will increase. Solutions will have to be found for environmentally acceptable disposal of the millions of tonnes of ash that will be produced annually.[4]

1.2 Study Objectives

Utilization of ash is the only economical solution to the problem of ash disposal. This study was undertaken to determine if fly ash can partially replace gypsum as a core material in the manufacture of gypsum wallboards. Not only will ash utilization aid in reducing the volume of waste to be disposed of, it should also reduce the cost of producing gypsum wallboards and slow down the depletion rate of gypsum as a natural resource. The use of fly ash in wallboards should also conserve energy consumption for the calcination and processing of gypsum.

1.3 Study Approach and Report Organization

The study was carried out in four phases and documented as explained below.

Phase I consisted of a literature review which focused on the effect of combining fly ash with gypsum and the suitability of using fly ash in residential building products. The results are presented in Sections 2.0 and 3.0.

In Phase 2 different tests on gypsum containing 0, 10, 20, 30 and 40 percent fly ash were conducted on three different samples of fly ash from three different power plants: Forestberg, Wabamun and Sundance. The selection of materials is described in Section 4.0. This phase included a visit to a gypsum wallboard manufacturing plant to study the actual manufacturing process and to identify appropriate tests on the gypsum. Tests included consistency, setting time and temperature-time relationships of the slurry, density, compressive strength and the rate of water absorption of the hardened material. Results of the above were analyzed and one mix with the optimum concentration of fly ash was tested for long term

strength and water absorption. The strength and water absorption of these mixes were recorded at ages of 1, 3, 7, 28, 56 and 180 days in the moist as well as oven-dried state. Densities of these hardened mixes were also determined. Samples from each of the mixes were examined with the help of the scanning electron microscope to investigate microstructural changes. Micrographs of selected specimens were also obtained. These tests are described in Section 5.0.

Phase 3 consisted of physical testing of gypsum wallboard samples with and without fly ash in accordance with CSA standards. Analysis of the test data in Phase 2 suggested that up to 30% of the gypsum may be replaced without any significant change in the properties of gypsum and, consequently, the core material of the wallboards. Therefore, one set of wallboard samples containing a replacement of 30% gypsum by fly ash was prepared for test purposes. To enable analysis of the effect of fly ash on various properties of the wallboards another set of wallboard samples without any fly ash was also prepared for testing. The materials used in preparing the samples are described in Section 6 and the preparation of samples is described in Section 7.

Phase 3 work consisted of carrying out appropriate tests of the wallboard samples. Tests included breaking strength, humidified deflection, core hardness, nailhead pull resistance, and thermal conductivity of the wallboard samples. All samples were prepared and tests were carried out in the laboratories of the Civil Engineering Department. Special moulds and jigs were fabricated for casting and testing the samples. The laboratory specimens were cured under predetermined temperature and humidity as specified in relevant CSA standards or as per practice of the manufacturers. The tests are described in Section 8. Test results are documented in Section 9 and in Appendix B.

Phase 4 consisted of an economic analysis of the partial replacement of gypsum with fly ash in wallboard and is documented in Section 10. Overall study conclusions are presented in Section 11.

2.0 EFFECT OF COMBINING FLY ASH WITH GYPSUM

According to ASTM C 618-80, (Figure 1 of Appendix A) a pozzolan is defined as a siliceous or siliceous and aluminous material which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties.

It is clear from the above definition of pozzolans, that Portland Cement minerals are not the only possible source of formation of the cementitious hydrates. There are many natural materials and industrial by-products capable of providing compounds which on hydration form the calcium silicate hydrates, calcium sulfo-aluminate hydrates, calcium aluminate hydrates, and calcium alumino ferrite hydrates of the type discussed above.[5] In fact, before the advent of the Portland Cement, mixtures of lime and volcanic ashes or calcined clays were routinely employed as hydraulic cements for making mortars and concretes. As defined earlier, such materials, which are mainly siliceous and aluminous are called "Pozzolans" and their reactivity with lime or similar material in presence of water, which is slow at ordinary temperature, is called "the pozzolanic property".

Not all siliceous and aluminous materials are pozzolanic. It is known the crystalline minerals, for instance, silica as quartz, alumina as corundum and alumino silicates such as sillimanite ($SiO_2 \cdot Al_2O_3$) and mullite

($3SiO_2 \cdot 2Al_2O_3$) do not react with lime solution at room temperature. But siliceous and aluminous materials present in noncrystalline form and as small particles can react with lime to form cementitious products. Therefore, for the purposes of evaluating the use of fly ash in gypsum, it should be noted that the mineralogical composition and particle size rather than the chemical composition would determine whether or not, or how fast a material can provide silica and alumina for cementitious reactions with gypsum.[6]

In the hydration process, calcium ions needed for formation of the cementitious hydrates become available with the dissolution of the principal components present in calcium sulphate ($CaSO_4 \cdot 2H_2O$). In gypsum the CaO present also becomes the source of calcium ions (see Table 1 of Appendix A). The difference between the "pozzolanic reaction" and cementitious reactions in the hydration of gypsum, therefore, lies mainly in the reaction rates, and not in the character of the hydration products. The pozzolanic reactions, like other chemical reactions, can be accelerated by temperature and by chemical accelerators such as alkalis and sulfates.

This leads to the conclusion that combining fly ash with gypsum is similar to the partial replacement of cement with fly ash and with similar hydration products. Fly ash, when used as a partial replacement of gypsum in wallboards, should act not only as a filler material but should also hopefully provide some additional cementitious material.

Fly ash has been used for partial replacement of cement in concrete for over five decades. In recent years up to 30 percent of the cement has been replaced with fly ash without any adverse effect on the environment or human health.[7]

3.0 SUITABILITY OF THE MATERIAL FOR USE IN RESIDENTIAL BUILDING PRODUCTS

The United States Environmental Protection Agency (EPA) regulations, in compliance of the Resource Conservation and Recovery Act (RCRA), were published in the Federal Register of the U.S. on 19 July 1980.[8] Excerpts from 40 CFR 261 at 45 FR 33084 19 May 1980, identify what solid wastes are subject to regulation as hazardous wastes. This regulation excludes residual wastes generated by the combustion of coal or other fossil fuels (namely fly ash, bottom ash, slag and fuel gas extractions) from consideration as hazardous waste.

Both the U.S. Environmental Protection Agency and the National Institute for Occupational Safety and Health (NIOSH) specify atomic absorption (AA) as the approved method for determining metal content of aqueous solutions. Atomic absorption methods are sensitive, rapid, reasonably precise and subject to few interferences.[9] Analytical data were obtained for 25 elements by AA. The results obtained in this study showed that agreement with atomic absorption spectrocopy is adequate to demonstrate compliance with EPA guidelines for most elements.

Alberta's "Hazardous Chemicals Act" was amended in 1982 and 1986 to include broad definitions for a "hazardous chemical" and hazardous waste: ie. A hazardous chemical is

> "any substance, class of substance or mixture of substances that is entering the environment in a quantity or concentration or under conditions that may constitute a danger to (i) the environment (ii) plant or animal life (iii) human health."

A "hazardous waste" is

> *"a hazardous chemical disposed of or to be disposed of as a waste". Under the Act the Lt. Governor of Council may make regulations establishing a schedule of hazardous chemicals and classifying those hazardous chemicals into such classes and subclasses as he thinks fit.*

On March 13, 1985, Alberta introduced the "Hazardous Waste Regulation" under the Hazardous Chemicals Act.[10] This regulation introduces waste manifesting, storage and bonding requirements. It also codifies Alberta's hazardous waste classification system. It builds on the above definition of "hazardous waste" by specifying which hazardous chemicals come under regulation control and what types of waste material are exempt.

Much of the provincial regulation closely mirrors the classification system and testing protocols employed in the federal TDG (Transportation of Dangerous Goods) regulations. The regulation exempts any waste that is not included in a table (Table 2 of Appendix A) which is identical to the extensive Schedule II of the federal TDG regulations. This regulation also exempts "fly ash waste, bottom ash waste, slag waste or flue gas emission control waste generated primarily from the combustion of coal or other fossil fuels".

Fly ash is now designated as a special waste. As mentioned earlier, "a hazardous waste is a chemical disposed of or to be disposed of as a waste:. The Resource Conservation and Recovery Act (RCRA), of the U.S.A. describes the term 'hazardous waste' as a solid waste or combination of solid wastes which because of its quantity, concentration or physical, chemical or infectious characteristics may:

(A) cause or significantly contribute to an increase in mortality or an increase in serious irreversible or incapacitating reversible illness or

(B) push a substantial present or potential hazard to human health or the environment when improperly treated, stored, transported or disposed of or otherwise managed.

The exact characteristics of a hazardous waste are outlined as follows in the same Act:

1) Ignitable waste which is defined as a liquid which has a flash point of less than 60°C and/or is not a liquid but is likely to cause fires.
2) Corrosive waste:
   a) Aqueous with a pH of less than or equal to 3.0 or a pH of greater than or equal to 12.0.
   b) Corrodes steel (SEA 1020) at a rate greater than 0.250 inches per year at a test temperature of 130°F.
3) Reactive waste:
   a) Normally unstable and/or reacts violently with water and/or produces toxic fumes with water.
   b) Is capable of detonation or explosion.
   c) Is a forbidden explosive.
4) Toxic waste is a waste which meets a set of extract criteria for a given set of substances.

On the basis of all these criteria fly ash and bottom ash are not considered as hazardous wastes. Above all use of fly ash over the years as a pozzolan or as a filler material has proven not to possess any of the characteristics of a hazardous waste.[11] In the present investigation the ash is planned to be used as a filler to replace part of the gypsum. Therefore, the fly ash particles will be encased in gypsum and will also hopefully react with gypsum on hydration. The question of leaching of any of the elements in the ash when covered with gypsum does not arise.

Fly ash is normally stable; neither does it react violently with water nor does it produce toxic fumes and is incapable of any detonation or explosion.

The regulations mentioned above were primarily intended for landfill and ash disposal sites to prevent contamination of groundwater.[12] Until now no restrictions have been formulated for the use of fly ash as a pozzolan or as a substitute of cement in concrete which may suggest any harmful effects on human health.

Lately fly ash is being used in combination with lime as a liner material to prevent contamination of groundwater from landfill and ash disposal sites. ASTM would not have specified fly ash for use in concrete in the first place if it was a hazardous material. Since 1948, many industrial, residential and office buildings, have been constructed with concrete containing fly ash as a pozzolan. Some examples are the Prudential Building, Blair Building, Marina City Complex, Sears Tower and Water Tower Place, all in Chicago. Fly ash was used in every ounce of concrete in the Sears Tower - the world's tallest building. Fly ash concrete was used in the foundations, the walls, the floors, and in the concrete for fire-proofing throughout the entire structure. There are no reports of any environmental pollution or health problems from any of the above mentioned structures.

ASTM standard specifications for fly ash and for raw or calcined and natural pozzolans for use as a mineral admixture in Portland Cement concrete dictate certain chemical and physical requirements to ensure compatibility with the properties of cement.[13]

Table 3 of Appendix A shows the range in values in percentages for the most prevalent constituents of coal ash as reported in literature. The abnormally high values for magnesium, sodium and sulfur trioxide are generally found only in lower grade coals, such as lignite. Fly ash can also contain trace concentrations of various elements including: antimony, arsenic, barium, berilium, boron, copper, flourine, lead, managanese, mercury, molybdenum, nickel, selenium, thallium, tin, titanium, uranium, vanadium and zinc. But the majority of these elements are bound with the siliceous materials which react with lime producing pozzolanic products. All the pozzolanic reaction compounds are insoluble in water. These pozzolanic products fill the voids between the particles of the matrix and thus encase the trace elements. This immobilizes even the trace elements and other compounds. Therefore, leaching of heavy metals is prevented. These elements apparently do not get released when fly ash reacts with lime or cement and are thus not leached from fly ash particles in concrete.

Studies conducted on fly ash concrete have also shown that addition of fly ash decreases permeability of concrete,[5] thereby decreasing penetration of air and water. Gassing off over time is also not a possibility when fly ash is used as pozzolan.[12] Leachate studies have shown that the principal ions contained in the leachate are calcium and sulphate, with smaller quantities of magnesium, sodium, potassium and silicate ions present in trace concentrations. These leachate studies were conducted on uncemented fly ashes. Fly ash in concrete or gypsum wallboards should not allow

leaching of undesirable elements. Besides, gypsum wallboards are not likely to be used in contact with water. Therefore, leaching of any elements appears not to be a relevant consideration.

Many studies have been conducted in recent years in an attempt to quantify the chemical constituents of coal ash. Table 5 of Appendix A is a composite of many of these studies, showing the maximum and minimum values found for 64 elements present in bottom ash and fly ash. These studies were made on different sizes and types of waste by-products generated by different power plants varying in megawatt output, furnace type, collector configuration, and of course, type of coal burned. The concentrations of trace elements of Canadian fly ashes including Sundance and Wabamun ashes selected for this research are presented in Appendix A, Table 5. These data were produced with regard to leachates. Since leaching out is not a problem here, there should not be any concern regarding these trace elements. Because of wide variations in coal and complications in stack sampling, as well as differences in analytical methods used, the data in Table 5 are intended merely to illustrate the tremendous variability in the concentration of elements from a given coal seam or basin. A sizeable variability may be expected in experimental results characterizing ash from a single power plant.

Polycyclic aromatic hydrocarbons (PAH) are generally toxic in nature.[11] Some are carcinogenic substances only if ingested. Analysis for the presence of polycyclic aromatic hydrocarbon (PAH) in ashes shows that concentrations were low, ranging generally from about 10 to 20 ppb. The total PAH concentration was estimated to be a maximum of about 0.2 ppm. This low concentration is not a health hazard. Table 6 of Appendix A gives the PAH concentrations found in the ash from one study. In any case the ash is not likely to be ingested and, therefore, no health hazard exists from use of ash in wallboards.

Radio nuclides are responsible for radiation problems. In case of fly ash they are not likely to cause any problem because of the small quantities present. Also the radio nuclides are enclosed in cementitious products, as mentioned earlier, once the ash is used as a pozzolan which further reduces any potential problem. No published report suggests any environmental or health effects due to such nuclides in concrete. The results of the analysis of specific concentration of the various radio nuclides in ash are given in Table 7 of Appendix A. Persistent and bio-accumulative substances and their concentrations responsible for classifying a waste as being hazardous and the proven carcinogenic substances are listed in Tables 8 and 9 in Appendix A. Since the ash will be used in the wallboards as a filler or pozzolanic material, the presence of such nuclides is not likely to pose any health hazards.

Review of relevant literature reveals no adverse effect on human health by the elements described above in the established quantities.

4.0 MATERIALS USED IN SAMPLE PREPARATION AND PRELIMINARY TESTING

Three different fly ashes, all from Alberta were used in this study. All the three fly ashes meet the requirements for CSA A 266.3, specification for "Mineral admixtures for use in portland cement concretes". Forestberg fly ash was supplied by Pozzolanic International. The other two ashes, generated in Wabamun and Sundance power plants, were supplied by Western Canada Fly Ash. Nonetheless, unclassified fly ash was used in the present study to minimize cost. In the cement concrete industry in Alberta, it is customary to use classified fly ash which contains less than certain weight percentage of particles coarser than 45 micro-metres.

The gypsum hemihydrate was supplied by the Construction Materials Group of Domtar Inc., Edmonton. This gypsum comes from the Stanford mountain range in the south eastern part of B.C. The quarried rock gypsum ($CaSO_4 \cdot 2H_2O$) is transported to Edmonton and then impurities such as limestone and shale are removed by selective crushing and screening. It is then calcined at 225° to 325°F to obtain the hemihydrate ($CaSO_4 \cdot \frac{1}{2}H_2O$) and then pulverized to the required size by sieving on No. 100 sieve with 0.15 mm opening. The calcined form of gypsum is commonly known as 'stucco'. An approximate chemical composition of calcined gypsum is given in Appendix A.

In the actual manufacture of gypsum wallboards, certain additives have to be added to modify or control its setting and hardening properties. Uncalcined gypsum is added to the calcined gypsum to increase the rate of setting. Potassium sulfate, starch and naptethalene sulphonate are also added to modify setting time and to control hardening of gypsum. Dispersing agents such as sodium naptethalene sulphonate and boric acid are also used in the manufacturing process to achieve the desired structure in hardened gypsum. Paper pulp and foam are added to reduce the weight of the wallboard and also to impart some flexibility to the board.

None of the chemical additives, except a foaming compound and starch, were used since this part of the study was only concerned with the interaction of gypsum and fly ash and changes to the properties of the gypsum hemihydrate as such. The additives are generally plant specific and may vary with the gypsum source, weather and wallboard specifications. More details about additives are given in a later section.

5.0 PRELIMINARY TESTS

As part of this study a visit to a gypsum wallboard manufacturing plant in Edmonton was undertaken. This plant belongs to the Construction Materials Group of Domtar Inc. Mr. Darryl Nielsen P.Eng., Technical Superintendent of the Gypsum Products Division, was kind enough to take us on a tour of the plant and also provide information and data about the manufacturing and testing procedures.

After careful observation of the manufacturing process and the behaviour of the gypsum during this process, it was decided to look into the effect of fly ash addition on gypsum slurry during setting and hardening of the core material during curing. Therefore, four basic properties of the stucco were investigated. These properties were, consistency of the slurry (stucco mixed with water), the setting time or initial hardening of the slurry, the temperature-time relationship which is an indicator of the setting property of the gypsum, and finally, the compressive strength of the hardened material. Densities of the wet and dry specimens, which are equally important, were also determined along with the rate of water absorption by the dried material.

Long-term tests to investigate the long term strength development and changes in water absorption levels due to addition of fly ash were also undertaken.

Gypsum without fly ash was used as the model or control mix in this investigation. Test procedures were adopted to simulate plant conditions or as per appropriate ASTM standards and are described further.

5.1 Consistency of the Slurry

The pouring consistency of calcined gypsum and water slurry is the basis on which the amount of water to be added to the stucco is determined.

Appropriate consistency is important to allow manufacture of wallboards of specified thickness. Standard specifications for the test to determine consistency of gypsum slurry are given in CSA A 82·20·3·M1977 and ASTM C472-84. This is a control test which is accurate enough to detect important changes in calcined gypsum consistency.

Gypsum-fly ash slurries were prepared with 0, 10, 20, 30 and 40% of each of the three different fly ashes. The water requirement for each of the mixes was determined and are given in Tables 10-12 of Appendix B. The data in Figures 2-5 show the resulting variation in consistency of the slurry as a function of the percentage of fly ash in the mix.

5.2 Setting Time

Setting time is determined by procedures described in ASTM C472-84. It is the time required for imbibition of water and partial dissolving of gypsum in water, colloid formation and crystallization of the hemihydrate ($CaSO_4 \cdot \frac{1}{2}H_2O$)[3]. Once this happens, the slurry loses its mobility and begins to transform into a hard and solid mass. Setting time is very important in the manufacture of the wallboard since it controls the time available for pouring and forming of wallboard after the stucco has been mixed with the water and additives.

The Vicat's apparatus and an electronic timing device were used to measure the time interval between mixing and setting of the gypsum. This time interval is called the setting time. Gypsum-fly ash mixes containing 0, 10, 20, 30 and 40% of each of the fly ashes were used and the setting time measured for each of the mixes. The test data are given in Tables 13-15 and plotted in Figures 6-9 of Appendix B.

5.3 Temperature-Time Relationship

Figures 10, 11 and 12 in Appendix B show the temperature rise with time on setting of gypsum and is a representation of the rate of the reaction between water and the hemihydrate. Gypsum-fly ash slurry samples containing 0, 10, 20, 30 and 40% of each of the three different fly ashes, with consistencies determined by the consistency tests, were used in this test.

When gypsum is mixed with water, there is a rise in temperature. Initially, the rise in temperature is gradual. After a while the rate of temperature rise increases significantly and a peak temperature is reached. The peak temperature is maintained for a while and then slowly drops. This temperature rise is an indicator of the setting property of the gypsum and is monitored closely since it is related to the rate of hardening of the slurry.

The expression, half-time ratio, is used to monitor the rate of temperature rise. Half-time between the initial and final temperature gradient is calculated as follows:

$$T_H = \frac{T_F - T_I}{2}$$

where

T_H = Half-time

T_F = Time taken to maintain final temperature constant

T_I = Time at which reaction process is activated initially.

Half-time ratio which is T_F/T_H, is required to be 2 at all times. The samples were enclosed in special chambers to prevent any heat loss due to conduction or convection.

A programmable thermo-scanner was used to record the temperatures at fixed intervals of time. Data from the scanner were then fed into a computer to produce time-temperature curves for the mixes.

5.4 Compressive Strength

Compressive strength is a good indicator of the durability of the material and it is also indirectly related to the flexural strength of the material. Compressive strength of gypsum-fly ash mixes was determined in accordance with ASTM C472 using 50 mm cube specimens.

Gypsum-fly ash specimens containing 0, 10, 20, 30 and 40% of each of the fly ashes were prepared and tested. Compressive strength data are presented in Tables 16, 17 and 18 of Appendix B. Percentage fly ash vs compressive strength curves are plotted in Figures 13, 14 , 15 and 16 of Appendix B. At least three cubes were tested for each of the mixes.

5.5 Density

Density of a material is its mass per unit volume. Densities were computed from the same specimens that were used for the compressive strength tests. The cubes were weighed individually before and after oven-drying prior to testing for compressive strength. The data or mass of individual cubes are presented in Tables 19, 20 and 21, and the wet and dry densities in Tables 22, 23 and 24 of Appendix B. The corresponding curves of density vs percentage fly ash are given in Figures 17, 18, and 19 of Appendix B. Densities were computed for all the mixes incorporating the three different fly ashes.

5.6 Long-term Testing

This testing was undertaken to investigate the long-term strength development in gypsum-fly ash mixes. For this purpose, a mix containing an

optimum percentage (30%) of Sundance fly ash was used. Compressive strength specimens (50 mm cubes) were prepared and placed in the fog room for curing under 100% humidity at 23°± 1°C. Cubes were also cast simultaneously to test the wet and dry densities and water absorption. All the specimens were dried in the oven at 42°C for 24 hours before being tested for compressive strength. The corresponding densities were also determined.

The tests were conducted at 1, 3, 7, 28, 56 and 180 days.

Water absorption tests were carried out on the 50 mm cube specimens. The specimens were cured for 1, 3, 7, 56 and 180 days, oven-dried and immersed in water at room temperature. The specimens were weighed at intervals of 1 hour until the mass became constant. Observations indicated that the specimens did not absorb any more water after 4 hours. Nonetheless, one specimen from each of the mixes was left in the water for 24 hours to determine any change in absorption rate. The data obtained are presented in Tables 25 and 26 and Figures 20-25 of Appendix B.

The compressive strength data are presented in Tables 27 and 28, the corresponding curves for change in strength with time are shown in Figure 26.

5.7 Micrographs

Samples were prepared from specimens tested for compressive strength for studying microstructural changes with the help of a scanning electron microscope. Micrographs of the different mixes were taken after thorough scanning and study of the specimen. Different magnifications and tube voltages were used for this purpose. Contact prints of some of the micrographs are given in Figure 27 of Appendix B.

6.0 MATERIALS USED IN PREPARATION OF WALLBOARD SAMPLES

All the three fly ashes used to prepare wallboard samples were unclassified fly ashes, ie. the ashes as produced and collected without separation of coarse particles etc. These fly ashes were from the same batch as the ones used in the previous phase. Forestberg fly ash was supplied by Pozzolanic International; the other two, Wabamun and Sundance fly ashes were supplied by Western Canada Fly Ash.

A fresh batch of gypsum hemihydrate was used to prepare the wallboard samples in this phase, since the age effects the strength of gypsum. This was again supplied by the Construction Materials Division of Domtar Inc., Edmonton. Since water required to produce a slurry of standard flowing consistency might change from batch to batch of the hemihydrate, consistency tests were repeated on this fresh batch. Results of these tests indicated no such change in the water requirement to produce a slurry of standard flowing consistency. All specimens for this phase of the study were, therefore, prepared with the same water content as in the previous phase.

Other materials used in the preparation of wallboard specimens included two layers of absorbent paper (which form the exterior surfaces of the board), paper pulp, starch and foam.

The paper, which comes in huge rolls, is more than 120 cm wide and resembles roofing paper. The outside surface of the paper is different from the inside. The fibres (grains) of the paper are aligned along the length of the paper and therefore, it can be torn lengthwise more easily than across its width. This alignment is important when considering the breaking strength of the wallboard specimens in the two different directions.

Starch in finely divided form is added to the slurry during mixing. This starch helps in achieving a better bond between the core material and the paper. The starch can be dissolved in water and becomes sticky to touch. The recommended starch dosage is about 0.029 kg/m^2 of wallboard. Both paper and starch were supplied by the Construction Materials Division of Domtar Inc., Edmonton.

A foaming compound and paper pulp is also added to gypsum slurry. The purpose of mixing paper pulp and foam is to reduce the density of the board and also to impart some flexibility to the board. Commercially available foam known as "Vanfoam" was used for making the wallboard specimens. Its chemical name is "Ammonium alkyl ethoxy sulphate". It is a clear amber liquid and is available in the concentrated form. The concentrated liquid is added to water in the required dosage and mixed thoroughly to obtain the foam.

Paper pulp is made from waste paper. Pulp is basically paper soaked in water. The recommended paper pulp dosage is about 0.270 kg/m^2. Paper pulp was prepared in the laboratory by using a domestic blender and mixing the soaked paper and water. The paper was cut into small pieces for effective soaking and mixing.

7.0 WALLBOARD SPECIMEN PREPARATION

It may be noted that the manufacture of wallboards in the plant involves expensive and sophisticated machinery. Use of such machinery in the laboratory for wallboard sample preparation is not feasible. Therefore, methods had to be devised to simulate industrial conditions in preparing wallboard specimens for laboratory testing.

In the industry the gypsum wallboards are prepared as described hereafter. The gypsum rock is crushed and calcined to hemihydrate and certain additives described further are added to modify and control its hardening properties. Uncalcined gypsum is added at the rate of 0.049 kg/m^2 to the hemihydrate initially to increase the rate of setting. Later, potassium sulphate (0.007 kg/m^2), starch (0.029 kg/m^2), potassium naphthalene sulphonate, trade name Hampex 80, (0.001 kg/m^2), sodium naphthalene sulphonate, trade name Disal, used as a dispersing agent (0.003 kg/m^2) and boric acid are added. Paper pulp is made from waste paper from the plant and mixed with the slurry. At this stage foam is also added and thoroughly mixed with the slurry in a mixer.

The slurry is then spread on the 120 cm wide paper which continuously moves on a conveyor. The paper is also heated by using a natural gas flame to drive out any moisture and straighten out any imperfections. The edges of the paper are then folded mechanically to form a trough to hold the slurry in between. Simultaneously another roll of paper with the same width as the trough is glued and sealed to the top of the trough containing the slurry. A continuous length of wallboard is formed in the form of a sandwich containing slurry between two sheets of paper. It is pressed between rollers to produce the required thickness. This wallboard so prepared is rolled on a conveyor which is about 150 m long. It takes about 4½ minutes for the board to cover the distance of about 150 m, and by this time it sets and dries out into a hardened wallboard. The board is now ready to be cut into the desired lengths.

The next important stage in the wallboard manufacture is the drying of the board. The drying zone is split into three different zones. These are huge ovens along the conveyor positioned one after the other. Before the

board enters the first zone, it is preheated to about 220°C. In Zone I, the temperature is about 295°C and it takes 10 minutes for the board to undergo drying in this zone. When it enters Zone II it is dried at a temperature of 280°C for about 11 minutes. Between Zone II and Zone III, there is an intermediate zone at a temperature of about 210°C. The third and final stage of drying occurs in Zone III at a temperature of 145°C and it takes about 13 minutes to complete drying in this zone. By the time the board emerges from Zone III, the temperature drops to slightly above the ambient temperature.

The final step is to finish the edges and seal them. The board is now ready to be stacked in the warehouse and shipped to different points of distribution.

To prepare the samples in the laboratory, special moulds had to be fabricated. Since it was impractical to make wallboards of standard lengths it was decided to make smaller specimens with standard thickness. Two moulds of different sizes were made for this purpose. The large mould had dimensions of 600 x 450 x 12.7 mm and the smaller one had dimensions of 400 x 300 x 12.7 mm. The base of the mould was made of 6.35 mm thick mild steel plate. The sides of the mould were also made of mild steel and could be rigidly fixed to the base plate. See Figure 28 of Appendix C for details. A trowel, plywood straightedge and a spatula were also used in sample preparation. The sides of the mould were also coated with a thin film of mineral oil for easy removal of the wallboard specimen from the mould.

Since the consistency of the slurry is important in forming the wallboard, the amount of water required to obtain the standard pouring consistency had to be carefully monitored. Water requirements to produce

standard pouring consistency vary with the type of fly ash and also the percentage of fly ash in the gypsum-fly ash mix. It may be noted that the water requirements for the three fly ashes with different percentages were established in the previous phase of this research (water/stucco ratios). For 30% replacement of gypsum with fly ash, the water/stucco ratios for the three different fly ashes were found to be:

Forestberg - 0.55
Wabamun - 0.58
Sundance - 0.58

Water/stucco ratio of 0.65 was used for mixes with pure gypsum. Even though the water/stucco ratios were established in the previous phase of this research, the consistency tests were repeated to confirm the results.

Predetermined quantities of gypsum, fly ash, paper, starch, and foam were weighed. Water required for preparing foam, pulp and slurry was weighed separately and used as described further. A sample mix proportion for 30% replacement by Sundance fly ash for making a 400 x 300 mm wallboard sample is given in Table 29 of Appendix C. Paper was cut into small pieces before mixing with water to produce pulp. A domestic blender was used to mix the paper and the required amount of water. A mixing time of 1-1½ minutes was sufficient to produce the pulp. Part of the water, (about 100 ml) required for the mix to prepare slurry was used for making the pulp. The pulp was kept in a separate beaker.

Foam was also produced similarly by mixing water and foaming compound. The foaming liquid was measured and added to about 100-150 ml water and mixed in the blender for a few seconds, until most of the water was foamed.

The two layers of paper required to hold the slurry were cut before hand and placed in an oven at 110°C for drying. This drying also helps the paper to straighten out since it comes in rolls and tend to become curved when cut into smaller sizes. Also, when the paper absorbs water it expands and, therefore, the paper had to be cut about 4 mm short in length and width to allow for expansion.

The bottom layer paper was placed in the mould before mixing the slurry. At this stage, the mixing of the slurry was initiated. Mixing was done in a plastic bowl in order to avoid sticking of the slurry on to the mixing bowl. The remaining water was poured into the mixing bowl and the paper pulp was added to it and mixed thoroughly. Starch was also dissolved in water before mixing and poured into the bowl. The prepared foam was also added to this mixture and stirred throughly. At this point, the fly ash-gypsum mix was added and mixed thoroughly with a spatula until all of it was dispersed throughout and formed an even mix. The slurry was then spread over the paper in the mould and levelled with a plywood straightedge. Immediately after the top layer paper was placed over this levelled slurry surface and pressed with a trowel to ensure that no air bubbles are left between the paper and the slurry surface. A small spatula was used to scoop away excess slurry squeezed out through the gap between the paper and the mould. The above mentioned operation has to be performed carefully and smoothly since it affected bonding between the core of the wallboard and paper. Uneven bonding may result in the paper being peeled off or in the board having reduced strength.

The board was left in the mould till the end of initial set when the top surface was again levelled smoothly with the trowel. The board

remained in the mould until it had hardened sufficiently to be removed from the mould.

The board was de-moulded after about 30-40 minutes and placed in an oven at 110°C until the board dried to constant weight. The board was then ready for conditioning and subsequent testing. Wallboard specimens were cast with and without fly ash. Ten specimens 400 x 300 mm and four specimens 600 x 450 mm were cast for each series (see Figs. 29 and 30 of Appendix C for photographs of the specimens).

8.0 TESTING OF THE WALLBOARD SPECIMENS

Testing of wallboard specimens was conducted in accordance with CSA Standard A 82.20.3-M, "Physical Testing of Gypsum Boards", which covers the methods for physical testing of gypsum boards, except for thermal conductivity tests where a test similar to the standard method of tests for cellular plastics by means of a probe (ASTM D2326) was adopted.

The main tests conducted on the wallboard specimens were as follows:

a) breaking strength (formerly known as flexural strength),

b) humidified deflection (similar to the effect of wetting),

c) core hardness ,

d) nailhead pull resistance ,

e) mass per unit area , and

f) thermal conductivity

8.1 Breaking Strength

This test involves 300 x 400 mm specimens with fibre of the paper parallel and perpendicular (cross grain) to the 400 mm dimension. Three specimens each were tested for both cases. The specimens were then weighed to within 1 g and conditioned at 22±2°C and 50±2 percent relative humidity until all specimens reached constant mass. The conditioning was done in a room where the temperature and humidity were controlled. It took about 3 days of curing or conditioning for the specimens to attain constant mass.

The Tinius-Olsen testing machine was used to test the breaking strengths of the wallboard specimens. Special jigs and fixtures had to be fabricated to test according to standard methods. In this case the set up involved two fixed parallel bearings 356 mm c/c to centrally support the specimen and a similar bearing that applies the load on the specimen midway between the supports. All bearings engage the full width of the specimen and are rounded to a radius of 3.1±0.1 mm. See Figs. 31 and 32 of Appendix C for details of the fixtures and setup.

The test load was applied at a uniform rate of 5 N/s until the specimen broke or failed. The average breaking force in each direction was computed and is reported as force applied parallel and across the grain of the paper surface in newtons.

Breaking strengths of wallboards containing fly ash as well as for wallboards made of pure gypsum are given in Table 30 of Appendix C.

8.2 Humidified Deflection

Humidified deflection evaluates the effect of moisture and temperature on the wallboards. High relative humidity and temperature results in the permanent deformation of the wallboard, and a creep effect similar to that

in concrete takes place, ie. if the wallboard specimen is supported on level bearing edges and left in an atmosphere of high relative humidity and temperature, it loses its planeness and deflects at the centre of the specimen.

To perform the humidified deflection tests two specimens 300 x 600 mm from each series were used. The specimens have the 300 mm dimension parallel to the fibre of the paper surface. These specimens were also conditioned at 22±2°C and 50±2 percent relative humidity for at least 24 hours before testing.

The wallboard specimen was suspended face down on two parallel and level bearing edges with 3 to 3.2 mm radii, spaced 580 mm apart. The bearings support the entire width of the specimen. This experiment was conducted in a special chamber constructed for this purpose with an atmosphere of 90±3 percent relative humidity and a temperature of 32±2°C, see Figure 33 of Appendix C for details of the setup.

The specimens were left in this atmosphere for 48 hours. The humidified deflection of the specimen was then measured as the distance between a straight edge placed on the top end edges of the specimen and the upper surface of the specimen at its centre.

The humidified deflection data are presented in Figure 34 of Appendix C as the average of these measurements to the nearest 1mm.

8.3 Core Hardness

The core of the wallboard is the material that is enclosed between the two layers of paper. The hardness of the core is an indirect measure of the strength of the core material. This strength along with the bond strength between the paper and core contribute to the overall strength of

the wallboard. Refer to Figures 35 and 36 of Appendix C for details of test setup.

The specimens for core hardness test were approximately 500 x 75 mm. The specimens were clamped in a fixed vertical position on 500 mm dimension edge. A steel punch 2.52±0.08 mm diameter with bearing surface machined to a 90° angle with reference to the punch centreline was used in this test. The punch was positioned on the top edge of the specimen in the testing machine (Tinius-Olsen) so that it was centered between the paper faces of the specimen. A force was applied at a uniform rate of 5 N/s. The core hardness is the force in newtons required to move the punch a distance of 13 mm into the core.

Three tests were conducted on one 500 mm edge of each of the specimen at least 100 mm apart and the results were averaged.

The core hardness data are reported as the average force in newtons in Table 31 of Appendix C.

8.4 Nailhead Pull Resistance

This test was conducted to evaluate the failure force when a nailhead is pulled or pushed through the wallboard specimen. Five specimens 150 mm x 150 mm from each series were tested. A 3 mm diameter pilot hole was drilled through the thickness of each specimen at its centre and perpendicular to the surface. The specimens were then conditioned to constant mass at 22±2°C and 50±2 percent relative humidity.

The key feature of this test involves a machine test "nail" having a nail shank of 2.50±0.08 mm diameter and a nailhead of 6.4±0.1 mm diameter. This nail is fitted into the cross-head or loading head of the testing

machine. The specimen is supported on a base plate having a 75 mm diameter hole in the centre. See Figures 37 and 38 of Appendix C for details.

The specimen is placed centrally over the 75 mm diameter hole of the baseplate and the test nail is lowered till the nail shank is inserted into the hole and the nailhead is flush with the surface of the specimen. A force is then applied to the nailhead at a uniform rate of 5N/s±10 percent until the specimen fails.

The nailhead pull resistance is the average force in newtons for the five specimens tested in each series. Results are reported in Table 32 of Appendix C.

8.5 Mass Per Unit Area

This is a simple test conducted to evaluate the mass per unit area of the wallboard with and without fly ash. The length, and breadth, of the wallboard specimens are measured and their mass recorded to the nearest 0.1 kg. The mass per unit area of each specimen is then calculated to two decimal places and reported as the average of all the specimens in the series in kg/m^2. See Table 33 of Appendix C for data on mass per unit area.

8.6 Thermal Conductivity

The wallboard is considered to be a thermal insulation with regard to the measurement of thermal conductivity. A thermal insulation is a material that is used to limit the amount of heat transferred between its two surfaces when a temperature difference is maintained between those two surfaces. The actual details of heat transfer within the interior involves a complicated combination of solid conduction, gaseous conduction, and

sometimes convection and radiation. It is important that the test simulates the performance of the insulating material or system under conditions that duplicate or approximate as closely as possible the actual thermal environment. In this case, measurement was made in a test situation which established a one-dimensional heat flow through the wallboard. The heat flow through the specimen is related to temperature differences between the surfaces and actual specimen geometry which in turn describe the thermal performance of the material. It may be noted that there is a wide difference between the theoretical property and actual use thermal performance. The approach to measuring of thermal conductivity in this case may not give a thermal conductivity value close to the theoretical value, but provides a better comparison of the thermal properties of the wallboard with and without fly ash.

Thermal conductivity is a property of the material measured by the ratio of steady state heat flux (time rate of heat flow per unit area) to the temperature gradient (temperature difference per unit length of heat flow path) in the direction perpendicular to the area.

ie. $q = k \cdot \Delta T/D$

where q = heat flux which is the power applied through unit area

k = thermal conductivity

ΔT = temperature differences

D = distance between the isothermal surfaces with temperature difference ΔT

Therefore, the parameters needed to be measured here are 'q' which can be calculated by knowing the power applied to the heating probe and ΔT, the

temperature difference. The thickness of the wallboard specimens is 12.7 mm, which is the value of D.

The test setup consists of a probe which is basically a heat source and a thermocouple attached to it to measure the temperature. The probe is about 12.7 mm in diameter and about 120 mm long. The wallboard specimen size was about 120 mm x 100 mm. The probe was sandwiched between two identical specimens with a third layer in the middle along the probe, consisting of two pieces of the same length of wallboard, and placed on either side of the probe. All of these were fastened together and placed in a box with fibre glass insulation to prevent any loss of heat. Another thermocouple was attached to the outer surface of the test specimen and the leads connected to a thermo-scanner which could give readouts of temperature differences between the two surfaces. See Figure 39 of Appendix C for details of setup.

A potentiometer was used to vary the voltage applied to the probe and a voltmeter to measure the applied voltage. Knowing the resistance of the probe heating element, the power applied to the probe could be calculated.

Measurements were taken when a steady state was reached, ie. the difference between the temperatures measured from the two surfaces became constant.

The results of the thermal conductivity tests are given in Tables 34 and 35 of Appendix C.

9.0 RESULTS AND DISCUSSION OF LABORATORY TESTS

The results of the tests conducted are discussed in the following sections.

9.1 Consistency Tests

An examination of data in Figures 2, 3, and 4 of Appendix B indicate that addition of fly ash reduces the amount of water required to maintain required consistency of the slurry. Apparently, fly ash remains inert initially, with only the water being adsorbed to the particles. It is, therefore, evident that most of the water in the gypsum-fly ash slurry is being used up by gypsum for re-hydration, ie. changing from the hemihydrate form ($Ca\ SO_4 \cdot \frac{1}{2}H_2O$) to the dihydrate form ($Ca\ SO_4 \cdot 2H_2O$).[4] As the percentage of fly ash in the mixture increases, there is a corresponding decrease in the quantity of gypsum in the mix. The inert fly ash retards the structure formation of the gypsum, i.e. the formation of the dihydrate crystals in the system.[14] This structure formation is what makes the material solid and imparts strength in the later stages. This is the main factor that governs the flow of the slurry. Therefore, as the percentage of gypsum decreases, there is reduced structure formation. Hence, the quantity of water required to maintain the flow decreases, and therefore, the water/stucco ratio decreases as the percentage of fly ash increases.

Comparison of the effect of three fly ashes on the consistency of slurry, shows that all the three types of fly ashes behave in a similar manner with the quantity of water varying only slightly from fly ash to fly ash. Wabamun and Surdance fly ashes maintained almost the same water/stucco ratio up to 30% replacement, and varied only slightly thereafter.

The variation in water/stucco ratio for mixes containing the Forestberg fly ash seems to be directly related to the replacement level.

9.2 Setting Time

The data in Figures 6, 7, 8 and 9 of Appendix B show that in general as the percentage of gypsum decreases with corresponding increase in the quantity of fly ash, the time taken for imbibition and partial dissolving of gypsum in water is reduced. Immediately following this stage, the next two stages, viz colloid formation and crystallization proceed without hindrance. The net result is that the setting time is reduced with increasing amount of fly ash.

Forestberg fly ash slightly retarded the later stages of colloid formation and crystallization. As the percentage of fly ash increased, there was increased retardation of crystallization, and as a result, the setting time increased with increasing amounts of fly ash.

It may be noted that the maximum variation observed was only 5 minutes between Forestberg and Sundance at 40% replacement, and only 3 minutes at 30% replacement. This is only a slight variation and may be altered to suit manufacturing conditions by the addition of accelerators or retarders.

9.3 Temperature-Time Relationship

As mentioned earlier, the temperature-time relationship is an indicator of the setting property of gypsum. This setting property is monitored with the help of temperature-time curve.

Examination of data in Figures 10, 11 and 12 of Appendix B suggests that the half-time ratios remained the same for all mixes for each of the fly ashes. There was only slight variation in the half-time ratios between the fly ashes. Half-time ratios of the different fly ashes are given as follows:

Forestberg = 2.0

Wabamun = 2.2

Sundance = 2.2

Specifications require the ratio to be 2 at all times. The slight variation is due to the behaviour explained in the previous section with regards to the setting time. These temperature-time curves are representations of the rate of reaction of the hemihydrate.

It may be noted that even though Forestberg fly ash retards the reaction or structure formation in gypsum, the rate of reaction is however only partially affected. In the case of Wabamun and Sundance fly ashes, a slightly higher ratio than 2.0 indicates a slightly faster reaction rate than the Forestberg fly ash but well within acceptable limits.

It may also be noted that the initial activation time of the reaction may vary even for different batches of gypsum as it is evident from the temperature-time curves in Figures 10 through 12 of Appendix B.

9.4 Compressive Strength

Compressive strength data indicate similar trends for all three fly ashes. Refer to Figures 13, 14 and 15 of Appendix B. In Figure 16 the data for all the three fly ashes are presented for comparison purposes.

Replacement of 10% gypsum by Forestberg fly ash reduces the strength only by about 2%. But at 20% replacement level, the strength increases rather slightly. Further replacement, ie 40%, reduced the strength by about 26%.

For the Wabamun fly ash, there was a loss of 4% of the strength at 10% replacement and a loss of 13% of the strength at 20% replacement. At 30% replacement, there was only a loss of about 6% of the strength of pure gypsum mix. At 40% replacement, there was a 30% loss in strength.

Compared to the other two fly ashes, Sundance fly ash produced only about 13% loss in strength at 40% replacement of gypsum. At 10% replacement there was a slight increase of about 2% in the strength. At 20 and 30 percent replacement the loss of strength was only 6% and 5% respectively.

These data clearly indicate that there is only very little loss of strength up to 30% replacement of gypsum as compared to the strength of the pure gypsum samples.

It may also be noted that compressive strength of pure gypsum may vary from batch to batch, as is evident from the compressive strength data in Figure 15. Therefore, up to 10% variation in the strength could be attributed to the variations in different batches of gypsum as is seen from data for zero percent replacement in Figure 16. It may therefore be concluded that up to 30% replacement by fly ash is likely to cause little or no change in strength of the core material in the wallboard.

9.5 Density

The data on dry and wet density of the core material are presented in Figures 17, 18, and 19 of Appendix B. Wet density is of little consequence. It was determined so as to compute the dry density. It is the dry density which provides an indication of the mass per unit volume of the finished core material in gypsum wallboards. Dry density data indicate only a slight increase in density at 30% addition of Forestberg fly ash; but, for the other two fly ashes the densities are slightly less or almost the same. Therefore, the wallboards containing up to 30% Sundance and Wabamun fly ashes will be slightly lighter than those made with pure gypsum as the core material.

9.6 Long-term Testing

Long-term test data for compressive strength of 50 mm cube specimens are given in Table 27 and Figure 26 of Appendix B. The data indicate that there is no significant change in the strength of the cube specimen with 30% Sundance fly ash. There was an increase of strength of only about 12% in 56 days and 16% in 180 days. Data on absorption of 50 mm cubes containing 30% Sundance fly ash and pure gypsum are given in Tables 25 and 26, respectively. Water absorption of specimens with or without fly ash does not seem to be affected by curing. Different specimens cured from 1 to 180 days exhibited water absorption of about 31 to 34%.

Comparison of absorption data of specimens containing fly ash to those without fly ash and cured for 1, 3, 7, 28, 56, and 180 days are given in Figures 20-25. The cubes made with pure gypsum always exhibited about 2% less water absorption than the cubes containing fly ash.

The data indicate that although the rate of absorption is almost the same for different ages of curing, the quantity of water absorbed increases as the period of curing increases. The quantity of water absorbed immediately by the control mix appears to be less than that of the gypsum-fly ash mixes, although the rate of absorption is almost the same. This may be due to the higher density of pure gypsum mix than the gypsum-fly ash mix. It is also possible that fly ash and gypsum react and produce slightly porous structure. Therefore, as the density decreases, absorption increases. This aspect needs to be investigated further.

The data also suggest that long-term curing does not seem to be of much importance in wallboards.

9.7 Photomicrographs

Compressive strength data indicates similar trends for all three fly ashes. Preliminary examination of cured gypsum and fly ash mixes under the electron microscope indicated that the fly ash particles were rather present as a filler material with very little hydration. In those mixes without the addition of fly ash, the hydrated gypsum crystal structure formation is continuous and it is this continuous structure that gives strength to the hardened mass. The hydrated crystals interlock with each other or in other words, molecular welding of the structural network with the formation of strong crystallized contacts occur.[14] Thus a system of continuous crystalline structure of calcium sulphate dihydrate ($CaSO_4 \cdot 2H_2O$) develops.

The loss in strength due to partial replacement of fly ash is possibly related to the interference of fly ash particles to this system. Not all particles exhibit this interference. Careful examination revealed some hydrated gypsum crystals actually embedded into the fly ash particles. Therefore, some bonding between fly ash and gypsum hydrates is evident.

Photomicrographs provided in Appendix B show the needle shaped crystals of calcium sulphate dihydrate and the spherical fly ash particles (Numbers 1-4). Close examination reveals that in some instances the gypsum hydrates either are embedded into the particles or attached to the surface of the fly ash particles (Numbers 1, 2 and 4). It can also be seen that hydration products have even occupied broken cenospheres in fly ash, see Micrograph No. 3, Figure 27. Growth of gypsum hydrates inside the fly ash particles suggests some interlocking and good mixing. Some of the interlocking crystalline material may even have been produced by hydration of cementing compounds in the fly ashes. Alberta ashes are known to produce such compounds on hydration which provide self-hardening property to these ashes.

All three fly ashes produced similar micrographs for the different mixes. Only micrographs of the Forestberg fly ash and gypsum mix are provided here. These results are based only on the analysis of limited number of specimens. Further studies are necessary to determine bonding of fly ash and gypsum hydrates.

9.8 Breaking Strength

Table 30 and Figure 40 of Appendix C indicate that the cross-grained strength of wallboard specimens with Wabamun and Forestberg fly ashes attained 2% lower breaking strength than the pure gypsum wallboard specimens. Wallboard specimens containing Sundance fly ash, on the other hand, exhibited 33% more breaking strength than the wallboard specimens containing pure gypsum.

CSA Standard A 82.27-M1977 specifies requirements for gypsum wallboards. The minimum strength requirement according to the specification for paper fibres perpendicular or cross-grain to bearing edges should be 41.66Z-41.66 newtons were Z is the board thickness in millimeters. For a 12.7 mm thick board this force is 487 N.

It is seen that even though the breaking strength of wallboards with Wabamun and Forestberg fly ashes is less than that of pure gypsum wallboards, it satisfies the minimum requirement specified by the CSA Standard.

For specimens tested with paper fibres parallel to bearing edges the minimum specified force should be 14 z, where z is the board thickness in millimeters. This force works out to be 178 N for a 12.7 mm thick board tested in this study. It may be seen from Figure 41 and Table 30 of Appendix C that wallboards containing pure gypsum gave lower strengths

compared to those containing fly ash in the core of the wallboard. This shows that the wallboard containing fly ash are stronger than conventional wallboards in what is considered to be the weak direction along the parallel grain.

9.9 Humidified Deflection

Figure 34 of Appendix C exhibits the results obtained from the humidified deflection test. It was seen that only wallboard specimens containing pure gypsum exhibited any deflection after 48 hours of curing in high humidity and temperature. Wallboards containing fly ashes did not show any deflection at all. CSA Standard requirement for humidified deflection is that the deflection shall not exceed 96-5z, when z is the board thickness in millimeters. This value equals to 32.5 mm for 12.7 mm thick boards.

These data from the humidified deflection test suggest that wallboards containing fly ashes possess a strong core and have good resistance to the detrimental effects of moisture and temperature. The data also suggest that the boards with fly ash would remain intact without any physical changes even when subjected to high humidity and temperature similar to those in the testing environment (93% relative humidity, 32±2°C).

9.10 Core Hardness

Results of core hardness tests presented in Table 31 and Figure 42 of Appendix C, on wallboard specimens with and without fly ash indicate that all the specimens exceed the minimum specified hardness of 67 N. Wallboard specimens with fly ash gave very high values compared to the specimens containing pure gypsum as the core material. Maximum average value was given by specimens with Forestberg fly ash (397 N) which is about 282% more than the pure gypsum specimen.

Wallboard specimens with Wabamun fly ash had an average core hardness value 243% more than pure gypsum wallboard specimens. The wallboards containing Sundance ash had an average core hardness value of 143% more than the pure gypsum wallboard.

Results suggest that the wallboard specimens containing fly ashes have a very strong core. It may be noted that high core hardness values do not necessarily mean that the boards should have high breaking strengths. It is the bond between the paper and the core material that imparts strength to the wallboard in addition to the minor contribution made by the core strength of the board. The high value of the core hardness will make the wallboard physically strong meaning that such wallboards will be superior to pure gypsum wallboards in withstanding impact forces.

9.11 Nailhead Pull Resistance

Data on nailhead pull resistance presented in Table 32 and Figure 43 of Appendix C, show that the wallboards prepared in the laboratory had very high values of nailhead pull resistance. CSA Standards specify a minimum force in newtons of 28Z, but not greater than 400 N, where Z is the board thickness in millimeters. The average failure force for wallboards containing Wabamun fly ash exhibited the highest resistance (645 N) which is 245 N more than the specified maximum value of 400 N.

The high values of nailhead pull resistance may be explained by the fact that all the wallboard specimens had very high core hardness values and therefore, high core strengths. Therefore, the core of the boards provide high resistance to the nailhead pulled or pushed through it.

The inconsistency of wallboard specimens made from Forestberg fly ash with the explanation given above may be due to specimen imperfections

caused by a concentration of air voids as a result of the addition of foam to the slurry. In general, if the specimen has high core hardness value it should exhibit high nailhead pull resistance.

9.12 Mass Per Unit Area

CSA Standards specify that the mass per unit area of the wallboard shall not be less than 0.616 z kg/m^2, where z is the board thickness in millimeters. ie. the mass should not be less than 7.823 kg/m^2 for a 12.7 mm thick board. Table 33 of Appendix C gives the mass per unit area of wallboard specimens with and without fly ash. Six 300 x 400 mm boards each were used to determine the mass per unit area in each series. The data indicate that all wallboards conform to CSA Standards. It may also be noted that wallboards with fly ash in the core have less mass per unit area than those made of pure gypsum. There is a reduction of 9 to 10% in the mass per unit area when fly ash was used to replace part of the gypsum. Therefore, use of fly ash could possibly reduce transportation costs of wallboards.

9.13 Thermal Conductivity

Thermal conductivity values obtained for wallboards with and without fly ashes are given in Tables 34 and 35, Figure 44 of Appendix C. The data indicate that wallboards containing fly ash have lower thermal conductivity than those containing only pure gypsum. This suggests that wallboards containing fly ash have better thermal insulating properties than those containing no fly ash in the core of the board. Wallboards containing Forestberg fly ash seem to have the best thermal insulating properties. Comparing data in Table 34 and Table 35, it may be inferred that the

conduction properties of the wallboards containing fly ash decrease as the temperature (T_1) increases, and hence, the thermal insulating properties improve considerably. Better thermal insulating properties may be of considerable importance in energy conservation when such boards containing fly ash are used in residential or commercial buildings.

10.0 ECONOMIC ANALYSIS

In an earlier part of this report it was pointed out that the earth's natural resources are limited and the depletion rate of these resources is alarmingly fast. Careful planning and controlled use of these resources, utilization of waste or by-products and recycling can solve some of this problem. Therefore, for the long term survival of mankind on this planet one must estimate and plan the use of the valuable resources based on time and the quantity of the resources available.

The law of supply and demand says that the more limited the supply at a given demand rate, the greater the cost or price of a raw material, commodity, or service. These costs are increased as money becomes more costly to borrow, and the materials required and skills needed to produce higher technology products become more sophisticated and more costly.

The productive activity of producing gypsum wallboards can be categorized under two basic outputs or areas of work, such as processes and products. Processes are industrial or commercial activities that alter one or more raw materials or substances into another useful product or substance through physical or chemical change. In this case, raw gypsum (raw material) is quarried, transported to a plant, calcined (chemically changed) to stucco, or the hemi-hydrate form of gypsum.

It is then used in the manufacture of the wallboard (product) and sold in quantity to consumers. The cost of a product is the summation of the resources that will actually be required to produce and market the product.

This part of the report estimates the cost savings achieved in production of wallboard through replacement of gypsum by fly ash.

The necessary items of a cost estimate of a product are man-hours, materials, indirect costs, administrative costs and profit. Only the material cost vary here and they will therefore be discussed further.

Since gas fired kettles are now commonly used to produce stucco from raw gypsum, operating data based on such kettles are used in calculations. Typical operating data are given in Table 36 of Appendix C.

For simplicity of calculations, a 24-hour period of wallboard production at a typical plant is considered.

24-hour Period of Wallboard Production - Materials & Cost

Quantity of wallboard produced = 750,000 sq. ft. (69,678 m^2)

Approximate wt. of stucco required to make 750,000 sq. ft. = 58 tonnes

Quantity of raw gypsum required to produce 58 tonnes of stucco = 70 tonnes

volume of natural gas consumed to convert this quantity of raw gypsum to stucco = 1688 m^3

If 30% by weight of stucco is replaced by fly ash,

new wt. of stucco in 69,678 m^2	= 40.6 tonnes
wt. of fly ash in 69,678 m^2	= 17.4 tonnes

Now, the quantity of raw gypsum required to produce 40.6 tonnes of stucco will become = 49 tonnes

Volume of natural gas required to convert 49 tonnes of raw gypsum to stucco will become = 1181 m^3

Volume of natural gas saved per day = 507 m^3

Quantity of raw gypsum saved per day = 21 tonnes

Quantity of stucco saved per day = 17.4 tonnes

(The quantity of fly ash used)

Cost savings on natural gas = 507 m^3

@ \$53/1000 m^3 = \$27

Cost of processing 21 tonnes of raw gypsum = \$630

(including cost of raw gypsum)

Cost of fly ash @ \$20/tonne = 17.4 x 20 = \$348

(delivered to plant in Edmonton)

Net savings in cost of raw materials per day = \$282

* (Cost of fly ash is likely to be much less than the cost of raw gypsum. Present cost is based on the assumption that the fly ash will be sold as a pozzolan in the way sold to ready mix concrete plants. Unclassified ash in large quantities may be available at much lower cost. The cost of adding fly ash in the wallboard manufacturing process is a capital cost and may only be determined by Process Engineers.)

Assuming that the plant produces wallboards 260 days per year, then the total savings in one year will be $73,320. Since there are many plants in Alberta the savings will be increased proportionately.

10.1 Energy and Natural Resource Consequence

It is estimated that Canada has about 370 million tonnes of gypsum as reserves. Canada and the United States jointly produce around 30% of the world's gypsum requirement. By such uncontrolled utilization of these reserves, a time when Canada might have to depend on other countries for its gypsum, is not far away. Gypsum production in Canada is around 1.5 million tonnes per year. Around 300 million square metres of wallboards are produced in one year in Canada. This means that about 250,000 tonnes of raw gypsum is being used in wallboard production each year. If the wallboard producers are able to adopt replacement of up to 30% of gypsum by fly ash, then about 75,000 tonnes of fly ash can be utilized annually, and this can considerably reduce the utilization of raw gypsum and also reduce the cost of producing wallboard.

It was shown earlier that around 507 cubic metres of natural gas is saved per day at a typical plant producing about 70,000 square metres of wallboard. Considering the total quantity of wallboard produced per year, this figure becomes about 2.2 million cubic metres of natural gas. This is not only a considerable amount of saving in energy costs, but also helps in conserving energy for other purposes.

In short, it can be seen that there are significant benefits to the industry and the consumer in partially replacing gypsum with fly ash in wallboard.

11.0 CONCLUSIONS

This study examined the feasibility of using fly ash as a partial replacement for gypsum in the manufacture of wallboards. Review of relevant literature and examination of data on various elements, radio nuclides etc. present in fly ash, did not indicate any adverse effect on human health. Leaching out of these elements is ruled out since there is little or no possibility of wallboards coming into direct contact with water.

The behaviour of gypsum and the corresponding changes to its characteristic properties due to the addition of fly ash was studied. Tests conducted indicate that fly ash may be used effectively to partially replace gypsum in the manufacture of the wallboards. Analysis of test data suggests that up to 30% of the gypsum may be replaced without any significant change in the properties of gypsum and therefore, the core material of the wallboards.

Data also suggest that fly ash particles remain as a filler material without diminishing much of the apparent strength. The fly ash also makes the boards lighter.

In some cases, wallboards containing fly ash exhibited properties superior to those containing only gypsum as the core material. Decreased humidified deflection, higher core hardness and impact resistance, higher nailhead pull resistance and weight reduction are characteristics builders and homeowners might find advantageous. The improved thermal insulating property due to the addition of fly ash in the wallboard core may assist in reducing indoor energy requirements and, therefore, possibly the energy costs in residential and commercial buildings.

Considering the amount of gypsum used in wallboard production, which is significant with regards to its total annual production, it can be seen the partial replacement of gypsum with fly ash helps in conserving this natural resource to a great extent. The consumers also may benefit by reduced cost of wallboard manufacture. There is likely to be considerable savings in energy requirements in the conversion of raw gypsum to stucco, thus, conserving non-replaceable natural gas in significant amounts. Thus, the utilization of fly ash will yield benefits to society, industry and the consumer.

BIBLIOGRAPHY

1. Joshi, R.C., "Geotechnical Aspects of Coal Ash Production, Disposal and Utilization", Proceedings: Workshop on Coal Ash and Reclamation - Alberta Land Conservation and Reclamation Council, Edmonton, April 1981, pp. 3-27.

2. Hansen, W.C., Offutt, J.S., Roy, D.M., Grutzeck, M.W., and Schatzlein, K.J., "Gypsum and Anhydrite in Portland Cement", United States Gypsum Company, Chicago, March 1988.

3. Bureau of Statistics' - Canada, Vol. 39, No:12, December, 1988.

4. Collins, J.P., and Sankin, W.P., "The Hazardous Waste Dilemma: Issues and Solutions", American Society of Civil Engineers, New York, N.Y., 1981.

5. Berry, E.E., and Malhotra, V.M., "Fly Ash for Use in Concrete Part II-A. A critical review of the effects of fly ash on the properties of concrete, CANMET Report 78-16, Canada Centre for Mineral and Energy Technology, Ottawa, January 1978.

6. Malhotra, V.M., "Fly Ash, Silica Fume, Slag and Other Mineral By-products in Concrete", Vol. II, American Concrete Institute, Detroit, S.P. 79, 1983.

7. Faber, J.H., Babcock, A.W., and Spencer, J.D., Proceedings: Fourth International Ash Utilization Symposium, St. Louis, MO, Energy Research and Development Administration, MERC/SP-76/4, Morgantown, W.Va., 1976.

8. Glenn, W.M., and Orchard, D., "Hazardous Waste Management Handbook - Fourth Edition, Corpus Information Services, Don Mills, Ontario, 1986.

9. Conway, R.A., and Malloy, B.C., "Hazardous Solid Waste Testing": First Conference, American Society for Testing and Materials, ASTM Special Technical Publication 760, December 1981.

10. Alberta Building Code, Alberta Labour, General Safety Services Division, Building Standards Branch, Edmonton, 1985.

11. Spencer, J.D., and Whieldon, Jr. C.E., Proceedings: Fifth International Ash Utilization Symposium, United States Department of Energy, Morgantown, West Virginia, February, 1979.

12. Tripodi, R.A., and Cheremisinoff, P.N., "Coal Ash Disposal: Solid Waste Inpact", Technomic Publication, 1980, Westport, CT 06880, 1980.

13. Standard in Building Codes, Vol. II, American Society for Testing and Materials 20th Edition, 1982, pp. 378-381.

14. Izmailova, V.N., Segalova, E.E., and Rebinder, P.A., "A Study of Structure Formation in Water Suspensions of Gypsum", National Research Council of Canada, Technical Translation, TT-672, Ottawa, 1957.

15. Verma, A., Draper, D.W., Mourits, F.M., Smail, D. and Manz, D.E., "Study of Potential Uses of Ash from Fossil-Fired Generating Stations", Saskatchewan Power Corporation, R & D, No.:4469-1979, August, 1979.

16. Kuntsevich, O.V., Aleksandrov, P.E., Ratinov, V.B., Rozenberg, T.I., and Bogautidinova, G.G., "The Theory of the Setting of Gypsum Bonding Materials", National Research Council of Canada, Technical Translation TT-685, Ottawa, 1957.

17. Sereda, P.J., Feldman, R.F., and Ramachandran, V.S., "Hydration of Gypsum Plaster by the Compact Technique", National Research Council of Canada, Ceramic Bulletin, Vol.:44, No.:2, 1965, pp. 151-155.

18. Stewart, R.D., "Cost Estimating", John Wiley & Sons, New York, 1982.

19. Matthews, L.M., "Estimating Manufacturing Costs, A Practical Guide for Managers and Estimators", McGraw-Hill Book Company, New York, 1983.

20. Statistics Canada - "Non Metallic Mineral Products Industries - Annual Census of Manufacturers", Ottawa, 1986.

APPENDIX A

Specifications, Properties and Chemical Components of Fly Ash

APPENDIX A

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Figure 1 - ASTM Standard Specification for fly ash Source: ASTM Standards in Building Codes - Volume II, 20th Edition, 1987.	A1
Table 1 - Properties of cement, gypsum and fly ash Source: 1. Malhotra, V.M., Fly Ash, Silica Fume, Slag, and Other Mineral By-Products in Concrete, Vol. II, American Concrete Institute, Detroit, S.P.7.9, 1983. 2. Tripodi, R.A. and Cheremisinoff, P.N., Coal Ash Disposal: Solid Waste Impacts, Technomic Publication, Westport, CT 06880, 1980.	A5
Table 2 - Hazardous waste types listed under Canada's Transportation of Dangerous Goods Act Source: William M. Glenn and Deborah Orchard, Hazardous Waste Management Handbook, Fourth Edition, Corpus Information Services, Don Mills, Ontario, 1986.	A6
Table 3 - Major constituents of coal ash Source: Raymond A. Tripodi, Paul N. Cheremisinoff, Coal Ash Disposal: Solid Waste Impacts, Technomic Publication, Westport, CT 06880, 1980.	A9
Table 4 - Chemical constituents of bottom ash and fly ash Source: Raymond A. Tripodi, Paul N. Cheremisinoff, Coal Ash Disposal: Solid Waste Impacts, Technomic Publication, Westport, CT 06880, 1980.	A10
Table 5 - Trace elements in fuel, fly ash and bottom ash Source: "Study of Potential Uses of Ash from Fossil-fired Generating Stations", Saskatchewan Power Cooperation, SPC RCD number 4469-1979, August, 1979.	A12
Table 6 - Estimated PAH concentration in ash Source: Raymond A. Tripodi, Paul N. Cheremisinoff, Coal Ash Disposal: Solid Waste Impacts, Technomic Publication, Westport, CT 06880, 1980.	A15
Table 7 - Contents of the various radionuclides in coal, bottom ash and fly ash Source: Raymond A. Tripodi, Paul N. Cheremisinoff, Coal Ash Disposal: Solid Waste Impacts, Technomic Publication, Westport, CT 06880, 1980.	A16

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Table 9 - Proven carcinogenic substances Source: Raymond A. Tripodi, Paul N. Cheremisinoff, Coal Ash Disposal: Solid Waste Impacts, Technomic Publication, Westport, CT 06880, 1980.	A17

Figure 1

Designation: C 618 – 80

An American National Standard

Standard Specification for FLY ASH AND RAW OR CALCINED NATURAL POZZOLAN FOR USE AS A MINERAL ADMIXTURE IN PORTLAND CEMENT CONCRETE[1]

This standard is issued under the fixed designation C 618; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This specification has been approved for use by agencies of the Department of Defense and for listing in the DoD Index of Specifications and Standards.

1. Scope

1.1 This specification covers fly ash and raw or calcined natural pozzolan for use as a mineral admixture in concrete where cementitious or pozzolanic action, or both, is desired, or where other properties normally attributed to finely divided mineral admixtures may be desired or where both objectives are to be achieved.

NOTE 1—Finely divided materials may tend to reduce the entrained air content of concrete. Hence, if a mineral admixture is added to any concrete for which entrainment of air is specified, provision should be made to assure that the specified air content is maintained by air content tests and by use of additional air-entraining admixture or use of an air-entraining admixture in combination with air-entraining hydraulic cement.

1.2 The values stated in inch-pound units are to be regarded as the standard.

2. Applicable Documents

2.1 *ASTM Standards:*

C 260 Specification for Air-Entraining Admixtures for Concrete[2]

C 311 Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland Cement Concrete[2]

3. Classifications

3.1 *Class N*—Raw or calcined natural pozzolans that comply with the applicable requirements for the class as given herein, such as some diatomaceous earths; opaline cherts and shales; tuffs and volcanic ashes or pumicites, any of which may or may not be processed by calcination; and various materials requiring calcination to induce satisfactory properties, such as some clays and shales.

3.2 *Class F*—Fly ash normally produced from burning anthracite or bituminous coal that meets the applicable requirements for this class as given herein. This class fly ash has pozzolanic properties.

3.3 *Class C*—Fly ash normally produced from lignite or subbituminous coal that meets the applicable requirements for this class as given herein. This class of fly ash, in addition to having pozzolanic properties, also has some cementitious properties. Some Class C fly ashes may contain lime contents higher than 10%.

NOTE 2—Currently the usual replacement of cement by Class C fly ash does not exceed 20).

4. Definitions

4.1 *pozzolans*—siliceous or siliceous and aluminous materials which in themselves possess little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form

[1] This specification is under the jurisdiction of ASTM Committee C-9 on Concrete and Concrete Aggregates, and is the direct responsibility of Subcommittee C 09.03.08 on Methods of Testing and Specifications for Admixtures.

Current edition approved May 30, 1980. Published July 1980. Originally published as C 618 – 68 T to replace C 350 and C 402. Last previous edition C 618 – 78.

[2] *Annual Book of ASTM Standards*, Part 14.

Figure 1 (continued)

compounds possessing cementitious properties.

4.2 *fly ash* – finely divided residue that results from the combustion of ground or powdered coal.

5. Chemical Requirements

5.1 Fly ash and natural pozzolans shall conform to the requirements as to chemical composition prescribed in Table 1. Supplementary optional chemical requirements are shown in Table 1A.

6. Physical Requirements

6.1 Fly ash and natural pozzolans shall conform to the physical requirements prescribed in Table 2. Supplementary optional physical requirements are shown in Table 2A.

7. Methods of Sampling and Testing

7.1 Sample and test the mineral admixture in accordance with the requirements of Method C 311.

7.2 Use cement of the type proposed for use in the work and, if available, from the mill proposed as the source of the cement, in all tests requiring the use of hydraulic cement.

8. Storage and Inspection

8.1 The mineral admixture shall be stored in such a manner as to permit easy access for proper inspection and identification of each shipment. Every facility shall be provided the purchaser for careful sampling and inspection, either at the source or at the site of the work as may be specified by the purchaser.

9. Rejection

9.1 The mineral admixture may be rejected if it fails to meet any of the requirements of this specification.

9.2 Packages varying more than 5 % from the stated weight may be rejected. If the average weight of the packages in any shipment, as shown by weighing 50 packages taken at random, is less than that specified, the entire shipment may be rejected.

9.3 Mineral admixture in storage prior to shipment for a period longer than 6 months after testing may be retested and may be rejected if it fails to meet the fineness requirements.

10. Packaging and Marking

10.1 When the mineral admixture is delivered in packages, the class, name, and brand of the producer, and the weight of the material contained therein shall be plainly marked on each package. Similar information shall be provided in the shipping invoices accompanying the shipment of packaged or bulk mineral admixture.

TABLE 1 Chemical Requirements

	Mineral Admixture Class		
	N	F	C
Silicon dioxide (SiO_2) plus aluminum oxide (Al_2O_3) plus iron oxide (Fe_2O_3), min, %	70.0	70.0	50.0
Sulfur trioxide (SO_3), max, %	4.0	5.0	5.0
Moisture content, max, %	3.0	3.0	3.0
Loss on ignition, max, %	10.0	12.0	6.0

Figure 1 (continued)

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TABLE 1A Supplementary Optional Chemical Requirements

NOTE – These optional requirements apply only when specifically requested

	Mineral Admixture Class		
	N	F	C
Magnesium oxide (MgO), max, %[A]	5.0	5.0	5.0
Available alkalies, as Na_2O, max, %[B]	1.50	1.50	1.50

[A] When the autoclave expansion or contraction limit of 0.8 % max is not exceeded, an MgO content above 5.0 % may be accepted. When the cement to be used in the work is known and available, the mineral admixture should be tested using that cement. Also refer to Table 2, footnote C.

[B] Applicable only when specifically required by the purchaser for mineral admixture to be used in concrete containing reactive aggregate and cement to meet a limitation on content of alkalies.

TABLE 2 Physical Requirements

	Mineral Admixture Class		
	N	F	C
Fineness:			
Amount retained when wet-sieved on No. 325 (45-μm) sieve, max, %[A]	34	34	34
Pozzolanic activity index:[B]			
With portland cement, at 28 days, min, percent of control	75	75	75
With lime, at 7 days min, psi (kPa)	800 (5500)	800 (5500)	800 (5500)
Water requirement, max, percent of control	115	105	105
Soundness:[C]			
Autoclave expansion or contraction, max, %	0.8	0.8	0.8
Uniformity requirements:			
The specific gravity and fineness of individual samples shall not vary from the average established by the ten preceding tests, or by all preceding tests if the number is less than ten, by more than:			
Specific gravity, max variation from average, %	5	5	5
Percent retained on No. 325 (45-μm), max variation, percentage points from average	5	5	5

[A] Care should be taken to avoid the retaining of agglomerations of extremely fine material.

[B] Neither the pozzolanic activity index with portland cement nor the pozzolanic activity index with lime is to be considered a measure of the compressive strength of concrete containing the mineral admixture. The pozzolanic activity index with portland cement is determined by an accelerated test, and is intended to evaluate the contribution to be expected from the mineral admixture to the longer strength development of concrete. The weight of mineral admixture specified for the test to determine the pozzolanic activity index with portland cement is not considered to be the proportion recommended for the concrete to be used in the work. The optimum amount of mineral admixture for any specific project is determined by the required properties of the concrete and other constituents of the concrete and should be established by testing. Pozzolanic activity index with portland cement is a measure of reactivity with a given cement and may vary as to the source of both the fly ash and the cement.

[C] If the mineral admixture will constitute more than 20 % of the cementitious material in the project mix design, the test specimens for autoclave expansion shall contain that anticipated percentage. Excessive autoclave expansion is highly significant in cases where water to mineral admixture and cement ratios are low, for example, in block or shotcrete mixes.

Figure 1 (continued)

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TABLE 2A Supplementary Optional Physical Requirements

NOTE – These optional requirements apply only when specifically requested

	Mineral Admixture Class		
	N	F	C
Multiple factor, calculated as the product of loss on ignition and fineness, amount retained when wet-sieved on No. 325 (45 μm) sieve, max, %[A]		255	
Increase of drying shrinkage of mortar bars at 28 days, max, %[B]	0.03	0.03	0.03
Uniformity Requirements:			
In addition, when air-entraining concrete is specified, the quantity of air-entraining agent required to produce an air content of 18.0 vol % of mortar shall not vary from the average established by the ten preceding tests or by all preceding tests if less than ten, by more than, %	20	20	20
Reactivity with Cement Alkalies:[C]			
Reduction of mortar expansion at 14 days, min, %	75		
Mortar expansion at 14 days, max, %	0.020	0.020	0.020

[A] Applicable only for Class F mineral admixtures since the loss on ignition limitations predominate for Class C.

[B] Determination of compliance or noncompliance with the requirement relating to increase in drying shrinkage will be made only at the request of the purchaser.

[C] The indicated tests for reactivity with cement alkalies are optional and alternative requirements to be applied only at the purchaser's request. They need not be requested unless the fly ash or pozzolan is to be used with aggregate that is regarded as deleteriously reactive with alkalies in cement. The test for reduction of mortar expansion may be made using any high-alkali cement in accordance with Method C 311, Section 35.1 if the portland cement to be used in the work is not known, or is not available at the time the mineral admixture is tested. The test for mortar expansion is preferred over the test for reduction of mortar expansion if the portland cement to be used in the work is known and available. The test for mortar expansion should be performed with each of the cements to be used in the work.

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Table 1 Properties of Cement[1], Gypsum[1] and Fly Ash[2]

Cement Material	Portland Cement	Blast-Furnace Slag	Gypsum	Fly Ash
Specific Gravity	3.16	2.89	2.31	2.0-2.5
Specific Surface (cm^2/g)	3180	4320	1500	1500-6500
Composition (%)				
L.O.I.	0.4	2.6	20.4	.1-10
insol.	0.0	---	0.3	
SiO_2	22.0	32.9	0.3	6.0-68
Al_2O_3	5.1	12.3	0.0	4.0-44
Fe_2O_3	3.3	0.9	0.1	1.0-44
MgO	1.3	6.0	0.0	0.1-14
CaO	64.7	41.0	32.6	0.2-52
SO_3	2.3	1.0	46.0	0.1-32
Mn_2O_3	---	0.5	---	---
Total	99.1	97.2	99.7	

Table 2
Hazardous Waste types listed under Canada's Transportation of Dangerous Goods Act

Waste Type 1 (The following spent halogenated solvents used in degreasing: tetrachloroethylene, trichloroethylene, methylene chloride, 1,1,1-trichloroethane, carbon tetrachloride, and chlorinated fluorocarbons; and sludges from the recovery of these solvents in degreasing operations)
Waste Type 2 (The following spent halogenated solvents: tetrachloroethylene, methylene chloride, trichloroethylene, 1,1,1-trichloroethane, chlorobenzene, 1,1,2-trichloro-1,2,2-trifluoroethane, ortho-dichlorobenzene, and trichlorofluoromethane; and the still bottoms from the recovery of these solvents)
Waste Type 3 (The following spent non-halogenated solvents: xylene, acetone, ethyl acetate, ethyl benzene, ethyl ether, methyl isobutyl ketone, n-butyl alcohol, cyclohexanone; and methanol; and the still bottoms from the recovery of these solvents)
Waste Type 4 (The following spent non-halogenated solvents: cresols and cresylic acid, nitrobenzene; and the still bottoms from the recovery of these solvents)
Waste Type 5 (The following spent non-halogenated solvents: toluene, methyl ethyl ketone, carbon disulphide, isobutanol, and pyridine; and the still bottoms from the recovery of these solvents)
Waste Type 6 (Wastewater treatment sludges from electroplating operations except for the following processes: (1) sulphuric acid anodizing of aluminum; (2) tin plating on carbon steel; (3) zinc plating (on a segregated basis) on carbon steel; (4) aluminum or aluminum-zinc plating on carbon steel; (5) cleaning/stripping associated with tin, zinc, and aluminum plating on carbon steel; and (6) chemical etching and milling of aluminum)
Waste Type 7 (Wastewater treatment sludges from the chemical conversion coating of aluminum).
Waste Type 8 (Spent cyanide plating bath solutions from electroplating operations except for precious metals electroplating spent cyanide plating bath solutions)
Waste Type 9 (Plating bath sludges from the bottom of plating baths from electroplating operations where cyanides are used in the process (except for precious metals electroplating bath sludges))
Waste Type 10 (Spent stripping and cleaning bath solutions from electroplating operations where cyanides are used in the process (except for precious metals electroplating spent stripping and cleaning bath solutions))
Waste Type 11 (Quenching bath sludge from oil baths from metal heat treating operations where cyanides are used in the process (except for precious metals heat treating quenching bath sludges))
Waste Type 12 (Spent cyanide solutions from salt bath pot cleaning from metal heat treating operations (except for precious metals heat treating spent cyanide solutions))
Waste Type 13 (Quenching wastewater treatment sludges from metal heat treating operations where cyanides are used in the process (except for precious metals heat and treating quenching wastewater treatment sludges))
Waste Type 14 (Cyanidation wastewater treatment tailing pond sediment from mineral metals recovery operations)
Waste Type 15 (Spent cyanide bath solutions from mineral metals recovery operations)
Waste Type 16 (Bottom sediment sludge from the treatment of wastewaters from wood preserving processes that use creosote and/or pentachlorophenol)
Waste Type 17 (Wastewater treatment sludge from the production of chrome yellow and orange pigments)
Waste Type 18 (Wastewater treatment sludge from the production of molybdate orange pigments)
Waste Type 19 (Wastewater treatment sludge from the production of zinc yellow pigments)
Waste Type 20 (Wastewater treatment sludge from the production of chrome green pigments)
Waste Type 21 (Wastewater treatment sludge from the production of chrome oxide green pigments (anhydrous and hydrated))
Waste Type 22 (Wastewater treatment sludge from the production of iron blue pigments)
Waste Type 23 (Oven residue from the production of chrome oxide green pigments)
Waste Type 24 (Distillation bottoms from the production of acetaldehyde from ethylene)
Waste Type 25 (Distillation side cuts from the production of acetaldehyde from ethylene)
Waste Type 26 (Bottom stream from the wastewater stripper in the production of acrylonitrile)
Waste Type 27 (Bottom stream from the acetonitrile column in the production of acrylonitrile)
Waste Type 28 (Bottoms from the acetonitrile purification column in the production of acrylonitrile)
Waste Type 29 (Still bottoms from the distillation of benzyl chloride)
Waste Type 30 (Heavy ends or distillation residues from the production of carbon tetrachloride)
Waste Type 31 (Heavy ends (still bottoms) from the purification column in the production of epichlorohydrin)

Table 2 (continued)

Waste Type 32 (Heavy ends from the fractionation column in ethyl chloride production)
Waste Type 33 (Heavy ends from the distillation of ethylene dichloride in ethylene dichloride production)
Waste Type 34 (Heavy ends from the distillation of vinyl chloride in vinyl chloride monomer production)
Waste Type 35 (Aqueous spent antimony catalyst waste from fluoromethanes production)
Waste Type 36 (Distillation bottom tars from the production of phenol/acetone from cumene)
Waste Type 37 (Distillation light ends from the production of phthalic anhydride from naphthalene)
Waste Type 38 (Distillation bottoms from the production of phthalic anhydride from naphthalene)
Waste Type 39 (Distillation light ends from the production of phthalic anhydride from ortho-xylene)
Waste Type 40 (Distillation bottoms from the production of phthalic anhydride from ortho-xylene)
Waste Type 41 (Distillation bottoms from the production of nitrobenzene by the nitration of benzene)
Waste Type 42 (Stripping still tails from the production of methyl ethyl pyridines)
Waste Type 43 (Centrifuge and distillation residues from toluene diisocyanate production)
Waste Type 44 (Spent catalyst from the hydrochlorinator reactor in the production of 1,1,1-trichloroethane)
Waste Type 45 (Waste from the product stream stripper in the production of 1,1,1-trichloroethane)
Waste Type 46 (Distillation bottoms from the production of 1,1,1-trichloroethane)
Waste Type 47 (Heavy ends from the heavy ends columns the production of 1,1,1-trichloroethane)
Waste Type 48 (Column bottoms or heavy ends from the combined production of trichloroethylene and perchloroethylene)
Waste Type 49 (Distillation bottoms from aniline production)
Waste Type 50 (Process residues from aniline extraction from the production of aniline)
Waste Type 51 (Combined wastewater streams generated from nitrobenzene/aniline production)
Waste Type 52 (Distillation of fractionating column bottoms from the production of chlorobenzenes)
Waste Type 53 (Separated aqueous stream from the reactor product washing step in the production of chlorobenzene)
Waste Type 54 (By-product salts generated in the production of MSMA and cacodylic acid)
Waste Type 55 (Wastewater treatment sludge from the production of chlordane)
Waste Type 56 (Wastewater and scrub water from the chlorination of cyclopentadiene in the production of chlordane)
Waste Type 57 (Filter solids from the filtration of hexachlorocyclopentadiene in the production of chlordane)
Waste Type 58 (Vacuum stripper discharge from the chlordane chlorinator in the production of chlordane)
Waste Type 59 (Wastewater treatment sludges generated in the production of creosote)
Waste Type 60 (Still bottoms from toluene reclamation distillation in the production of disulfoton)
Waste Type 61 (Wastewater treatment sludges from the production of disulfoton)
Waste Type 62 (Wastewater from the washing and stripping of phorate production)
Waste Type 63 (Filter cake from the filtration of diethylphosphorodithioic acid in the production of phorate)
Waste Type 64 (Wastewater treatment sludge from the production of phorate)
Waste Type 65 (Wastewater treatment sludge from the production of toxaphene)
Waste Type 66 (Untreated process wastewater from the production of toxaphene)
Waste Type 67 (Heavy ends or distillation residues from the distillation of tetrachlorobenzene in the production of 2,4,5-T)
Waste Type 68 (2,6-Dichlorophenol waste from the production of 2,4-D)
Waste Type 69 (Untreated wastewater from the production of 2,4-D)
Waste Type 70 (Wastewater treatment sludges from the manufacturing and processing of explosives)
Waste Type 71 (Spent carbon from the treatment of wastewater containing explosives)
Waste Type 72 (Wastewater treatment sludges from the manufacturing, formulation, and loading of lead-based initiating compounds)
Waste Type 73 (Pink/red water from TNT operations)
Waste Type 74 (Dissolved air flotation (DAF) float from the petroleum refining industry)
Waste Type 75 (Slop oil emulsion solids from the petroleum refining industry)
Waste Type 76 (Heat exchanger proposed bundle cleaning sludge from the petroleum refining industry)
Waste Type 77 (API separator sludge proposed from the petroleum refining industry)
Waste Type 78 (Tanks bottoms (leaded) from the petroleum refining industry)
Waste Type 79 (Ammonia still lime sludge from coking operations)

Table 2 (continued)

Waste Type 80 (Emission control dust sludge from the production of steel in electric furnaces)
Waste Type 81 (Spent pickle liquor from steel finishing operations)
Waste Type 82 (Sludge from lime treatment of spent pickle liquor from steel finishing operations)
Waste Type 83 (Acid plant blowdown slurry sludge resulting from the thickening of blowdown slurry from primary copper production)
Waste Type 84 (Surface impoundment solids contained in and dredged from surface impoundments at primary lead smelting facilities)
Waste Type 85 (Sludge from treatment of process wastewater and/or acid plant blowdown from primary zinc production)
Waste Type 86 (Electrolytic anode slimes/sludges from primary zinc production)
Waste Type 87 (Cadmium plant leach residue (iron oxide) from primary zinc production)
Waste Type 88 (Emission control dust/sludge from secondary lead smelting)
Waste Type 89 (Waste leaching solution from acid leaching of emission control dust/sludge from secondary lead smelting)
Waste Type 90 (Brine purification muds from the mercury cell process in chlorine production where separately prepurified brine is not used)
Waste Type 91 (Chlorinated hydrocarbon wastes from the purification step of the diaphragm cell process using graphite anodes in chlorine production)
Waste Type 92 (Wastewater treatment sludge from the mercury cell process in chlorine production)
Waste Type 93 (Solvent washes and sludges, caustic washes and sludges, or water washes and sludges from cleaning tubs and equipment used in the formulation of ink from pigments, driers, soaps, and stabilizers containing chromium and lead)
Waste Type 94 (Wastewater treatment sludges generated during the production of veterinary pharmaceuticals from arsenic or organo-arsenic compounds)
Waste Type 95 (Distillation tar residues from the distillation of aniline-based compounds in the production of veterinary pharmaceuticals from arsenic or organo-arsenic compounds)
Waste Type 96 (Residue from the use of activated carbon for decolorization in the production of veterinary pharmaceuticals from arsenic or organo-arsenic compounds)
Waste Type 97 (Decanter tank tar sludge from coking operations)

Table 3 Major Constituents of Coal Ash) (As Reported in Four Sources)

	Min.	Max.
SiO	6.0	68
Al O	4.0	44
FE O	1.0	44
CaO	0.2	52
TiO	0.4	4.17
MgO	0.1	14
Na O	0.09	28
K O	0.1	4
SO	0.1	32
C & Volatiles	0.1	20

Table 4 *Chemical Constituents of Bottom Ash and Fly Ash*

	Flyash (ppm) Bottom ash/Slag (ppm) Min.	Max.	Min.	Max.
Aluminum (Al)	11,500.0	144,000.0	88,000.00	135,000.0
*Antimony (Sb)	0.8	1,000.0	0.14	12.0
*Arsenic (¼as)	2.3	1,700.0	0.98	40.0
Barium (Ba)	96.0	13,900.0	500.00	4,000.0
*Beryllium (Be)	1.0	1,000.0	3.00	10.6
Bismuth	10.0	30.0	–	–
Boron (b)	<10.0	3,000	70.00	300.0
Bromine (Br)	0.3	670.0	2.00	11.0
*Cadmium (Cd)	0.1	250.0	< 0.50	< 250.0
Calcium (Ca)	5,400.0	177,000.0	8,400.00	50,600.0
Cerium (Ce)	28.0	320.0	84.00	310.0
Cesium (Cs)	1.4	17.0	7.70	–
Chlorine (cl)	13.0	25,000.0	<1,100.00	1,800.0
*Chromium (Cr)	11.0	7,400.0	15.00	270.0
Cobalt (Co)	6.0	1,500.0	3.60	380.0
*Copper (¼cu)	30.0	3,020.0	2.80	720.0
Dysprosium (Dy)	4.2	31.0	37.00	–
Europium (Eu)	1.0	16.7	1.11	15.0
Fluorine (F)	0.4	624.0	10.60	100.0
Gallium (ga)	10.0	10,000.0	5.00	64.0
Germanium (Ge)	<10.0	11,000.0	–	–
Gold (Au)	0.004	0.5	0.10	–
Hafnium (Hf)	1.4	11.0	4.60	8.5
Indium (In)	0.1	2.4	1.00	–
Iodine (I)	0.1	200.0	9.50	–
Iron (Fe)	7,800.0	289,000.0	27,000.00	203,000.0
Lanthanum (La)	17.0	270.0	155.00	75.0
*Lead (Pb)	3.1	1,600.0	5.00	35.0
Lithium (Li)	77.0	120.0	60.00	78.9
Lutetium (Lu)	0.41	4.3	2.50	–
Magnesium (Mg)	4,900.0	60,800.0	4,500.00	32,500.0
Manganese (Mn)	31.0	4,400.0	100.00	720.0
*Mercury (Hg)	0.01	22.0	0.01	< 4.0
Molybdenum (Mo)	6.5	500.0	3.00	45.0
*Nickel (Ni)	1.8	8,000.0	10.00	700.0
Niobium (Nb)	16.0	<20.0	12.00	<20.0
Palladium (Pd)	0.2	–	–	–
Phosphorus (P)	600.0	2,500.0	300.00	1,600.0
Platinum (Pt)	0.7	–	–	–
Potassium (K)	1,534.0	34,700.0	7,300.00	15,800.0
Rhodium (Rh)	0.02	–	–	–
Rubidium (Rb)	25.0	300.0	48.00	300.0
Samarium (Sm)	3.7	43.0	8.20	46.0

(Continued)

Table 4 · *Chemical Constituents of Bottom Ash and Flyash (Continued)*

	Fly Ash (ppm)		Bottom Ash/Slag (ppm)	
	Min.	Max.	Min.	Max.
*Selenium (Se)	1.2	< 500.0	0.08	7.7
Silicon (Si)	196,000.0	271,000.0	180,000.00	273.000.0
*Silver (Ag)	1.0	50.0	25.00	–
Sodium (Na)	1,180.0	20,300.0	1,800.00	13,100.0
Sulfur (S)	0.11	0.25	0.06	0.09
Strontium (Sr)	40.0	9,600.0	170.00	1,800.0
Tantalum (Ta)	0.5	2.6	0.95	1.03
Tellerium (Te)	0.11	10.0	< 0.02	–
Thallium (Ti)	1.1	100.0	0.25	–
Thorium (Th)	1.8	68.0	12.00	15.0
Tin (Sn)	<3.0	4,250.0	–	–
Titanium (Ti)	400.0	15,900.0	3,300.00	7,210.0
Tungsten (W)	2.9	42.0	38.00	–
Uranium (U)	0.8	30.1	6.78	14.9
Vanadium (V)	20.0	1,180.0	44.00	670.0
Ytterbium (Yb)	1.7	23.0	18.009	.0
Yttrium (Y)	21.0	800.0	30.00	44.0
*Zinc (Zn)	14.0	13,000.0	24.00	950.0
Zirconium (Zr)	100.0	5,000.0	220.00	–

Table 5 Trace elements in fuel, fly ash and bottom ash of Canadian coal- and oil-fired thermal generating stations (in ppm) [a]

	HAT CREEK			BATTLE RIVER			H.R. MILNER			SUNDANCE			WABAMUN		
	C[b]	FA	BA	C	FA	BA[c]	C[b]	FA	BA[c]	C[b]	FA	BA	C[b]	FA	BA
Antimony	<1.0						0.25		<0.1	<1.0			<1.0		
Arsenic	9.18					21[d]	<0.4		15[d]	1.09	21		2.36	17	
Barium	235					2,317	363		748	617			264		
Beryllium						74			86		4			3	
Bismuth						248			289						
Boron						1,056[d]			213[d]		251			415	
Bromine	<1.0						4.47			<2.0			<1.0		
Cadmium						14			16		<1.3			<1.2	
Cerium	22.4						10.7			14.8			11.9		
Cesium															
Chlorine	<0.3						355		550	<400			<300		
Chromium	137	68	137			63	<0.5		143	<3.0	11		2.29	15	
Cobalt	9.85					124	1.53		109	1.39	9		1.43	10	
Copper						24			73		22			17	
Dysprosium															
Europium	<0.2						0.18			<0.4			0.20		
Fluorine									8.6						

[a] All data in this table are supplied by the respective utilities, except where indicated otherwise. The symbols C, O, FA, BA and CA are abbreviations for coal, oil, fly ash, bottom ash and coal ash respectively.

[b] Data from Environment Canada (1979).

[c] This report; analyses performed by Dept. of Geochemistry, University of Regina, Saskatchewan; Saskatchewan Research Council, Saskatoon, Saskatchewan; Powell Analytical & Consulting Services, Calgary, Alberta.

[d] Based on partial digestion.

[e] Fly ashes in this column are not available, as they are not collected at present.

[f] Coal ash from lignite samples throughout mining area.

Table 5 (continued) Trace elements in fuel, fly ash and bottom ash of Canadian coal- and oil-fired thermal generating stations (in ppm) [a]

	HAT CREEK			BATTLE RIVER			H.R. MILNER			SUNDANCE			WABAMUN		
	C[b]	FA	BA	C	FA	BA[c]	C[b]	FA	BA[c]	C[b]	FA	BA	C[b]	FA	BA
Gadolinium	<100						<30			<30			<20		
Gallium									<100						
Germanium									<0.5						
Gold						<11			<11						
Hafnium	1.12						1.19			0.99			1.07		
Holmium															
Iodine	<10						<20			<30			<20		
Lanthanum	3.52						8.17			8.10					
Lead						54			54		44			25	
Lithium						32			44						
Lutetium															
Manganese	442	253	822			432	11.5		236	56.8	156		144	131	
Mercury									0.24		0.07			<0.05	
Molybdenum						31			34		15			22	
Neodymium															
Nickel						70			107		17			18	
Niobium						19			15						

[a] All data in this table are supplied by the respective utilities, except where indicated otherwise. The symbols C, O, FA, BA and CA are abbreviations for coal, oil, fly ash, bottom ash and coal ash respectively.

[b] Data from Environment Canada (1979).

[c] This report; analyses performed by Dept. of Geochemistry, University of Regina, Saskatchewan; Saskatchewan Research Council, Saskatoon, Saskatchewan; Power Analytical & Consulting Services, Calgary, Alberta.

[d] Based on partial digestion.

[e] Fly ashes in this column are not available, as they are not collected at present.

[f] Coal ash from lignite samples throughout mining area.

Table 5 (continued) Trace elements in fuel, fly ash and bottom ash of Canadian coal- and oil-fired thermal generating stations (in ppm) [a]

	HAT CREEK			BATTLE RIVER			H.R. MILNER			SUNDANCE			WABAMUN	
	C[b]	FA	BA	C	FA	BA[a]	C[b]	FA	BA[a]	C[b]	FA	BA	C[b]	FA BA
Palladium														
Rubidium									<5					
Samarium	2.48					31			123					
Scandium	11.6						1.67			0.18			1.11	
Selenium	<5.0						2.88			1.51			1.67	
Silver							<3.0		1.8	<2.0	<1.3		<3.0	<1.4
Strontium	<200					<2.7			<2.7		<1.0			<1.0
Tantalum	<1.0					1,850	<500		295	<500			<400	
Tellurium							<0.6			<1.0			<1.0	
Terbium						35[d]			20[d]					
Thallium														
Thorium														
Tin									1.3					
Tungsten						<190			<190		<5			<5
Uranium														
Vanadium									3.2					
Ytterbium						127			310		44			40
Yttrium														
Zinc						51			27					
Zirconium						37			104		26			44
						305			176					

[a] All data in this table are supplied by the respective utilities, except where indicated otherwise. The symbols C, O, FA, BA and CA are abbreviations for coal, oil, fly ash, bottom ash and coal ash respectively.

[b] Data from Environment Canada (1979).

[c] This report; analyses performed by Dept. of Geochemistry, University of Regina, Saskatchewan; Saskatchewan Research Council, Saskatoon, Saskatchewan; Power Analytical & Consulting Services, Calgary, Alberta.

[d] Based on partial digestion.

[e] Fly ashes in this column are not available, as they are not collected at present.

[f] Coal ash from lignite samples throughout mining area.

Table 6 *Estimated PAH Concentration in Ash*

PAH	Concentration ppb*
Naphthalene	8.3
2-Methylnaphthalene	5.0
1-Methylnaphthalene	5.2
Biphenyl	10.3
1,6- and/or 1,3-Dimethylnaphthalene	T
2,6-Dimethylnaphthalene	T
1,5- and/or 2,3-Dimethylnaphthalene	T
9,10-Dihydroanthracene	12.6
Phenanthrene	17.6
2-Methylanthracene	9.1
1-Methylphenanthrene	<24.8
Fluoranthene	<13.4
Pyrene	<19.0
1,2-Benzofluorene	36.8
2,3-Benzofluorene	11.8
1-Methylpyrene	T
Picene	T
Total	<0.2 ppm

*Trace = Trace
< = Interference allows estimate only of maximum possible concentration.

Table 7. *Contents of the Various Radionuclides in Coal, Bottom Ash and Fly Ash*

	ppm						pCi/g			
	U	Th	K	^{40}K	^{232}Th	^{226}Ra	^{210}Pb	^{226}Ra	^{238}U	^{235}U
Plant A[2]										
Coal	0.71	1.6	860	0.73	0.17	0.17	0.26	0.21	0.24	0.012
ESP fly ash	5.6	15	9400	8.1	1.7	1.7	1.4	2.3	1.9	0.093
Bottom ash	4.6	14	7900	6.8	1.5	1.5	0.58	1.9	1.5	0.072
Plant B[3]										
Coal	2.5	5.0	1660	1.4	0.56	0.55	0.68	0.64	0.85	0.037
ESP fly ash	11	22	7400	6.3	2.4	2.4	2.2	2.9	3.5	0.14
Bottom ash	8.4	19	7200	6.2	2.2	2.1	0.84	2.5	2.8	0.11
Scrubber ash	11	22	7200	6.2	2.5	2.5	2.8	3.0	3.6	0.14
Plant B[4]										
Post-ESP (Stack) Flyash (mmd)[5]										
17 um	16	25	8200	7.0	2.8	2.7	4.3	3.3	5.4	0.17
6 um	20	31	8600	7.3	3.3	3.5	10	4.6	6.8	0.28
3.8 um	30	36	8600	7.4	3.3	4.0	14	5.3	10	0.39
2.5 um	36	38	8100	7.0	3.3	4.2	17	5.9	12	0.50

[1] 10.20% propagated 1 error from the mean.
[2] Samples from Plant A; input coal contains 11.3% H O, 9.2% ash, and 0.52% sulfur.
[3] Samples from plant B; input coal contains 6.8% H O, 23.2% ash, and 0.46% sulfur.
[4] mmd = mass median diameter determined by centrifugal sedimentation.

Table 8 - Persistent and Bioaccumulative Substances and their Concentrations Responsible for Classifying a Waste as being Hazardous

	Concentration (ppm)		Concentration (ppm)
Aldrin	0.14	Lead and compounds (inorganic)	5
Antimony and compounds	100	Lindane	0.4
Arsenic and compounds	5	Mercury and compounds	0.2
Barium and compounds (exluding Basite)	100	Mirex	0.5
		Methoxychlor	10
Beryllium and compounds	1	Molybdenum and compounds	350
Cadmium and compounds	1	Nickel and compounds	20
Chlordane	0.3	Pentachlorophenol	1
Chromium and Chromium (VI) compounds	5	Polybrominated biphenyls (PBBs)	5
		Polychlorinated biphenyls (PCBs)	5
Chromium and Chromium (III) compounds	25	Polychlorinated terphenyls (PCTs)	5
Cobalt and compounds	80	Selenium and compounds	1
Copper and compounds	15	Silver and compounds	5
DDT, DDE, DDD (TDE)	0.1	Thallium and compounds	5
2, 4 - Dichlorphenonyacetic acid	10	Toxaphene	0.5
Dieldrin	0.1	Trichloroethylene	0.5
Dioxin (TCDD)	0.003	2, 4, 5 - Trichlorophenoxyacetic acid	1
Endrin	0.02		
Fluoride Salts	180	Vanadium and compounds	24
Heptachlor	0.3	Zinc and compounds	20
Kepone	0.5		

Table 9 — Proven Carcinogenic Substances

Any waste containing a combined wet weight concentration of 1 or more of the following substances at, or in excess of 1000 ppm is classified as Class 9.3, I.D. number 9300.

2-Acetylaminofluorene (2-AAF)
Acrylonitrile
4-Aminodiphenyl (4-ADP)
Benzidine
bis-(Chloromethyl) ether (BCME)
Chloromethyl methyl ether (CMME)
3,3'-Dichlorobenzidine (DCB)
4-Dimethylaminoazobenzene (DAB)
Ethyleneimine (EI)
4,4-Methylene-bis-2-chloroaniline (MOCA)
1-Naphthylamine (1-NA)
2-Naphthylamine (2-NA)
4-Nitrobiphenyl (4-NBP)
N-Nitrosodimethylamine (DMN)
2-Propiolactone (2-PL)
Vinyl chloride (VCM)

APPENDIX B

Preliminary Tests on Stucco

APPENDIX B

		Page No.
Figures 2-5	- Variation in consistency of slurry due to the effect of the three different fly ashes	B1 -B4
Figures 6-9	- Setting time of gypsum - effect of the three different fly ashes	B8 -B11
Figures 10-12	- Temperature-time relationship : effect of the three different fly ashes in the gypsum-fly ash mix	B15-B17
Figures 13-16	- Compressive strength of 50 mm cubes of gypsum-fly ash mixes	B18-B21
Figures 17-19	- Wet and dry densities of gypsum-fly ash mixes	B25-27
Figures 20-25	- Long-term test. Water absorption curves of gypsum-fly ash cubes cured for 1, 3, 7, 28, 56, and 180 days	B36-41
Figure 26	- Long-term test. Compressive strength of 50 mm cubes of gypsum-fly ash mixes cured for 1, 3, 7, 28, 56 and 180 days	B43
Figure 27	- Micrographs of different fly ash gypsum mixes	B44
Tables 10-12	- Variation in consistency of slurry due to the effect of the three different fly ashes	B5 -B7
Tables 13-15	- Setting time of gypsum - effect of the three different fly ashes	B12-B14
Tables 16-18	- Compressive strength of 50 mm cubes of gypsum-fly ash mixes	B22-B24
Tables 19-21	- Data of mass of individual cubes of gypsum-fly ash mixes	B28-30
Tables 22-24	- Wet and dry densities of gypsum-fly ash mixes	B31-33
Tables 25-26	- Long term test data - 30% Sundance fly ash - Gypsum mix - water absorption of 50 mm cube specimens	B34-35
Table 27	- Long-term compressive strength of 30% Sundance fly ash - gypsum mix cured for 1, 3 7, 28, 56, and 180 days	B42

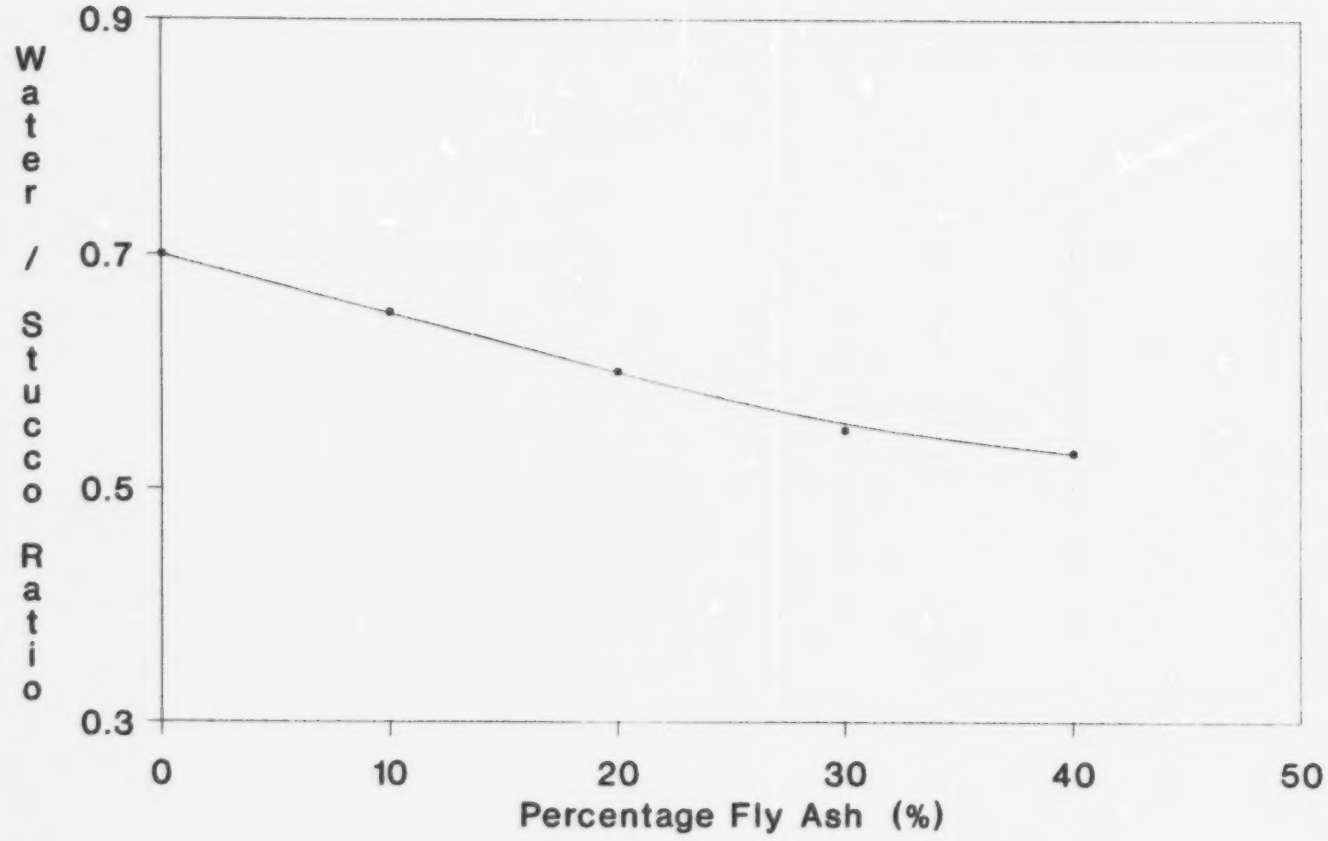


Figure 2: Variation in consistency of slurry due to the effect of Forestberg fly ash

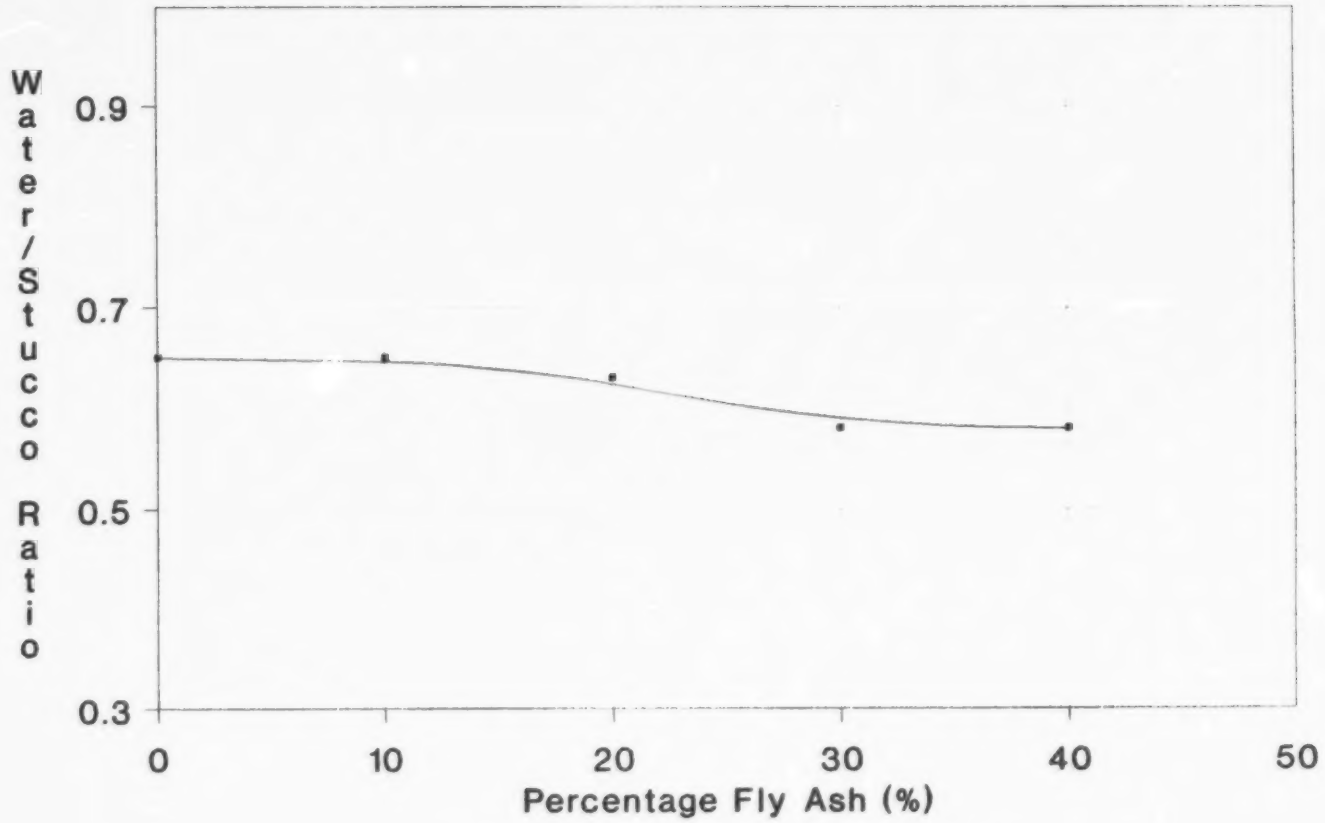


Figure 3: Variation in consistency of slurry due to the effect of Wabamun fly ash

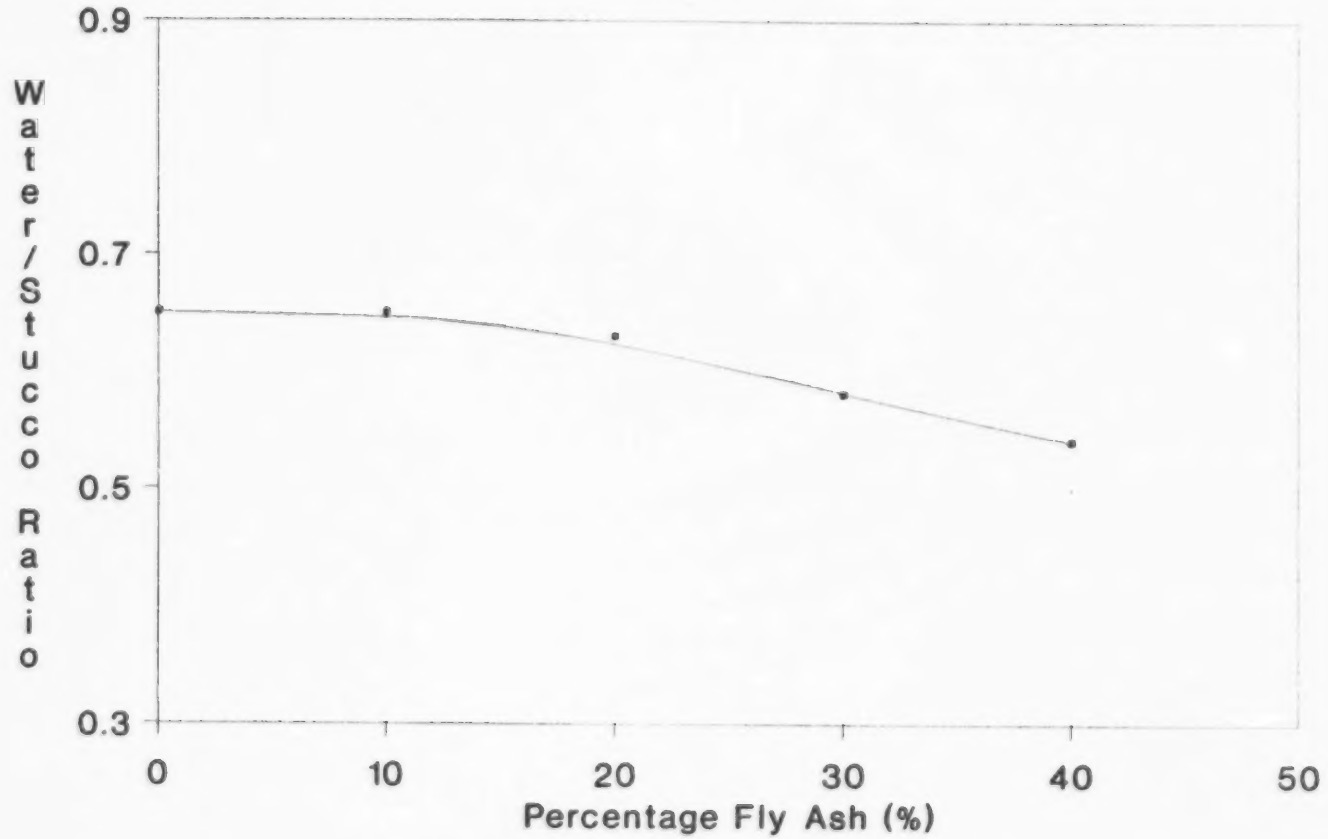


Figure 4: Variation in consistency of slurry due to the effect of Sundance fly ash

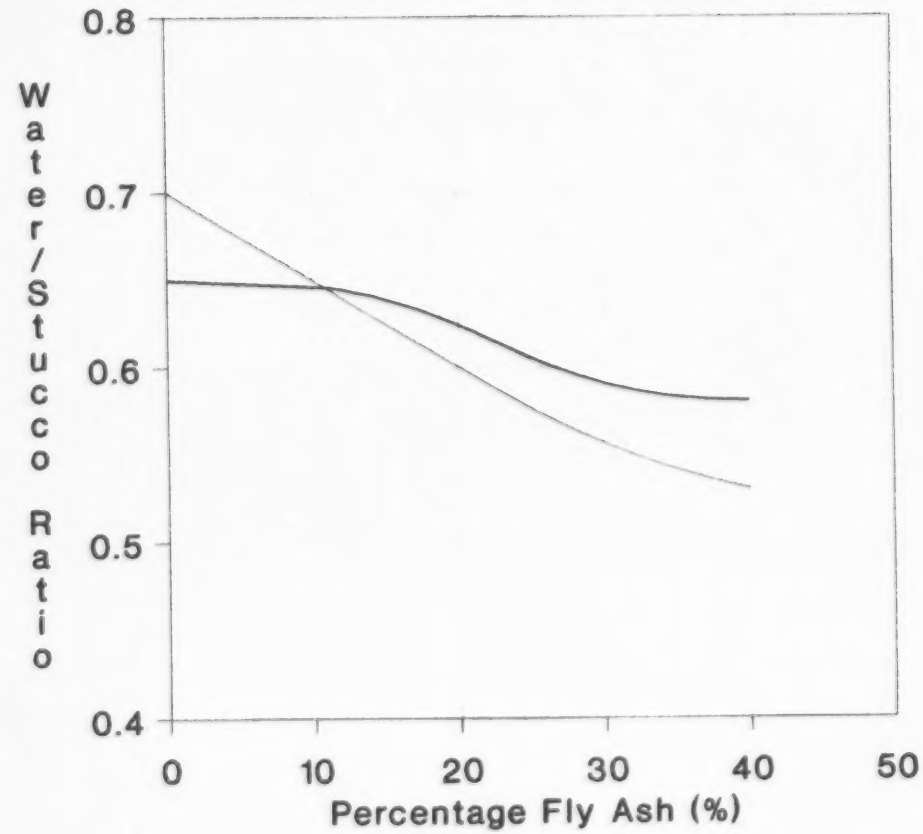


Figure 5: Variation in consistency of slurry- Comparison of the effects of three different fly ashes

Table 10

VARIATION IN CONSISTENCY OF SLURRY WITH INCREASING AMOUNTS OF FLY ASH
Forestberg Fly Ash

Percentage Fly Ash	Weight (g) Gypsum	Weight (g) Fly Ash	Total Wt. (g)	Water added (ml)	Water/Stucco Ratio
0	50	0	50	35.0	0.70
10	45	5	50	32.5	0.65
20	40	10	50	30.0	0.60
30	35	15	50	27.5	0.55
40	30	20	50	26.5	0.53

Table 11

VARIATION IN CONSISTENCY OF SLURRY WITH INCREASING AMOUNTS OF FLY ASH
Wabamun Fly Ash

Percentage Fly Ash	Weight (g) Gypsum	Weight (g) Fly Ash	Total Wt. (g)	Water added (ml)	Water/Stucco Ratio
0	50	0	50	32.5	0.65
10	45	5	50	32.5	0.65
20	40	10	50	31.5	0.63
30	35	15	50	29.0	0.58
40	30	20	50	29.0	0.58

Table 12

VARIATION IN CONSISTENCY OF SLURRY WITH INCREASING AMOUNTS OF FLY ASH
Sundance Fly Ash

Percentage Fly Ash	Weight (g) Gypsum	Weight (g) Fly Ash	Total Wt. (g)	Water added (ml)	Water/Stucco Ratio
0	50	0	50	32.5	0.65
10	45	5	50	32.5	0.65
20	40	10	50	31.5	0.63
30	35	15	50	29.0	0.58
40	30	20	50	27.0	0.54

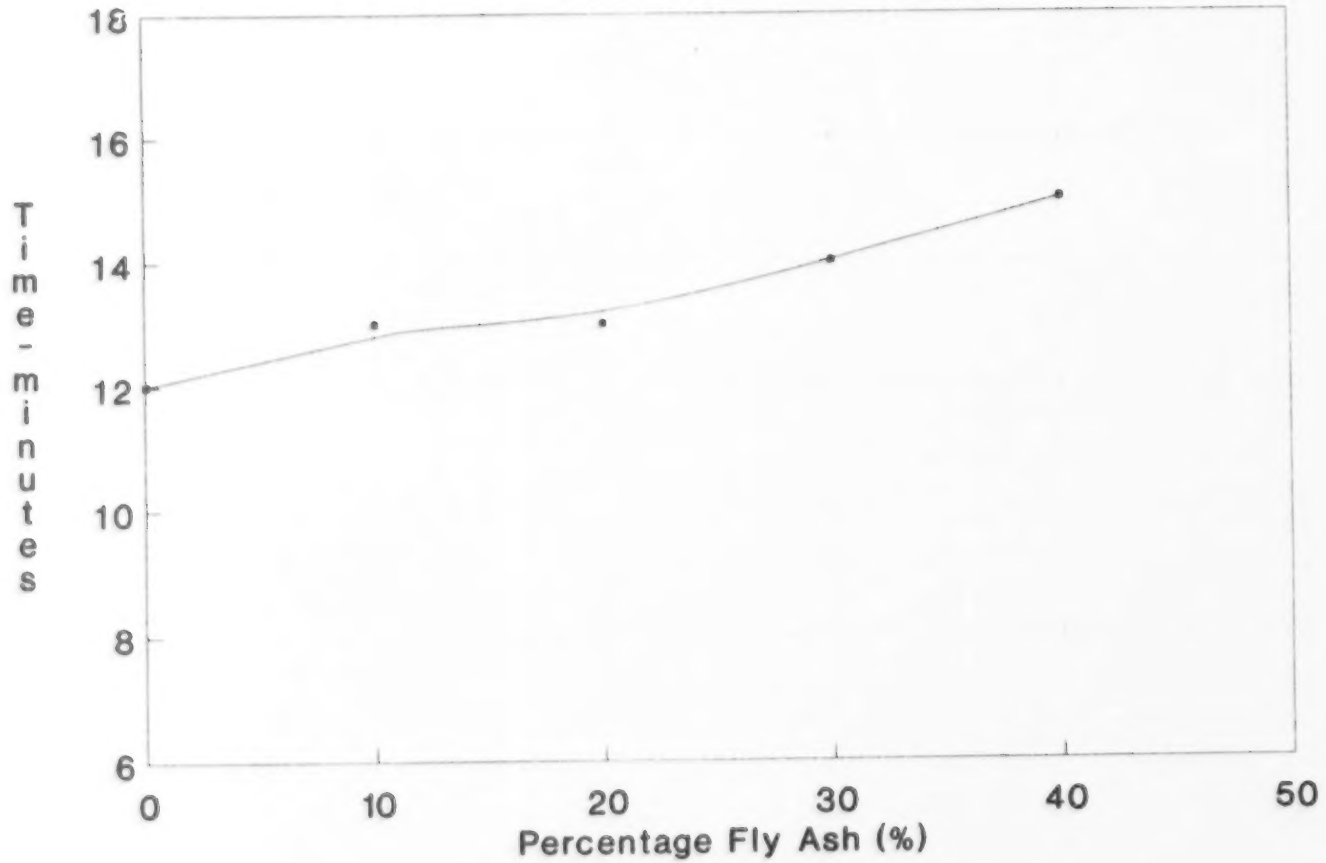


Figure 6:Setting time of gypsum - Effect of Forestberg fly ash

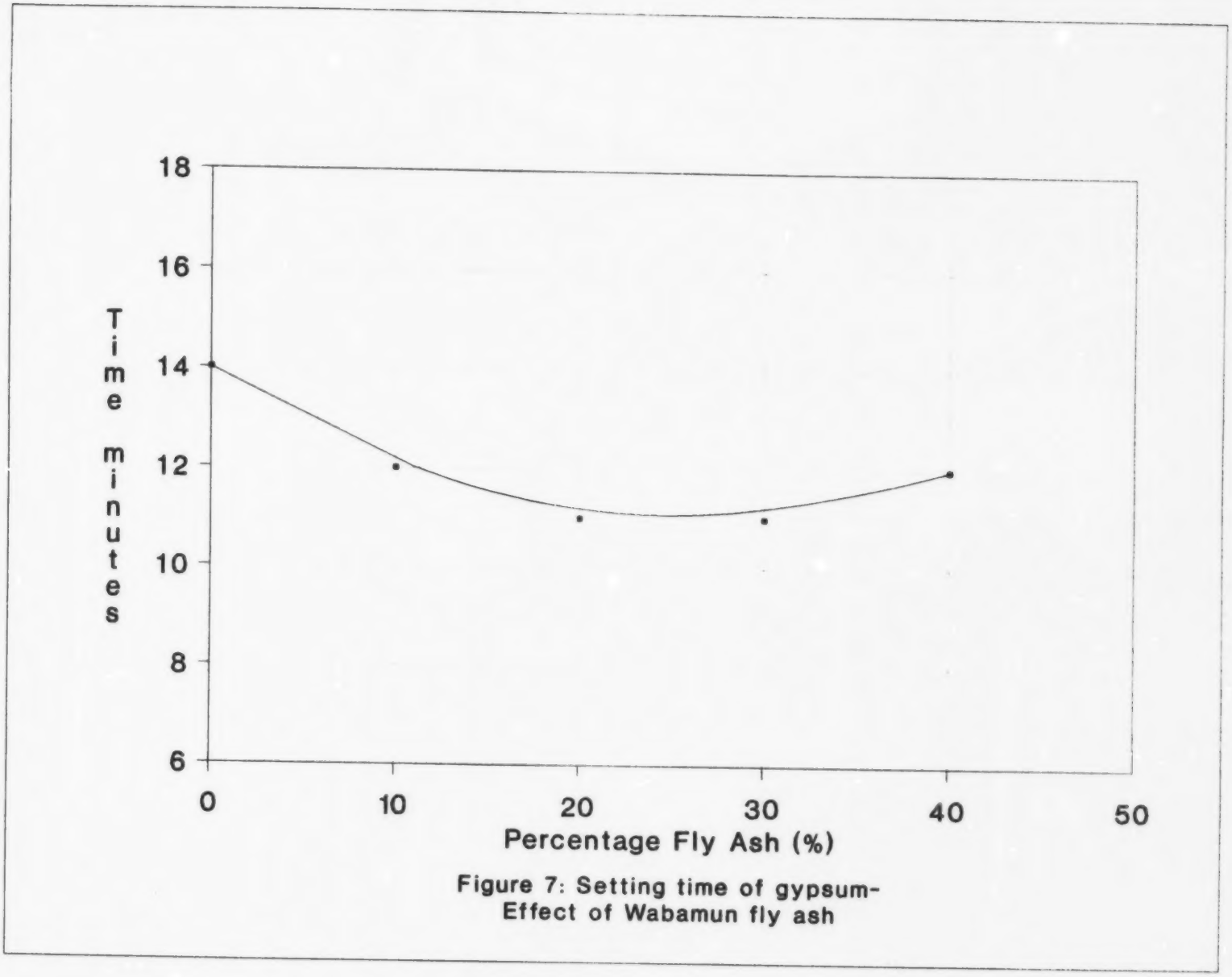


Figure 7: Setting time of gypsum-
Effect of Wabamun fly ash

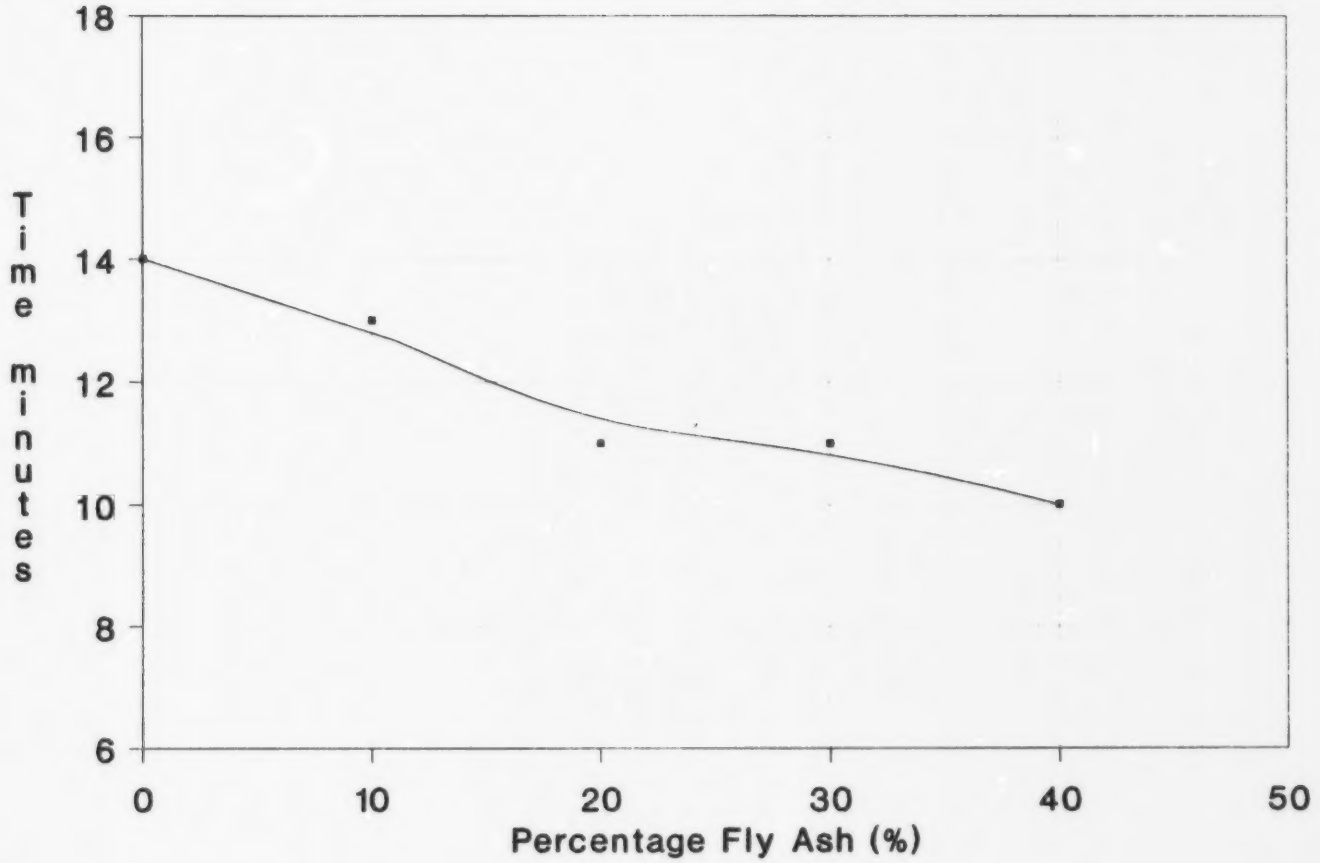


Figure 8: Setting time of gypsum-
Effect of Sundance fly ash

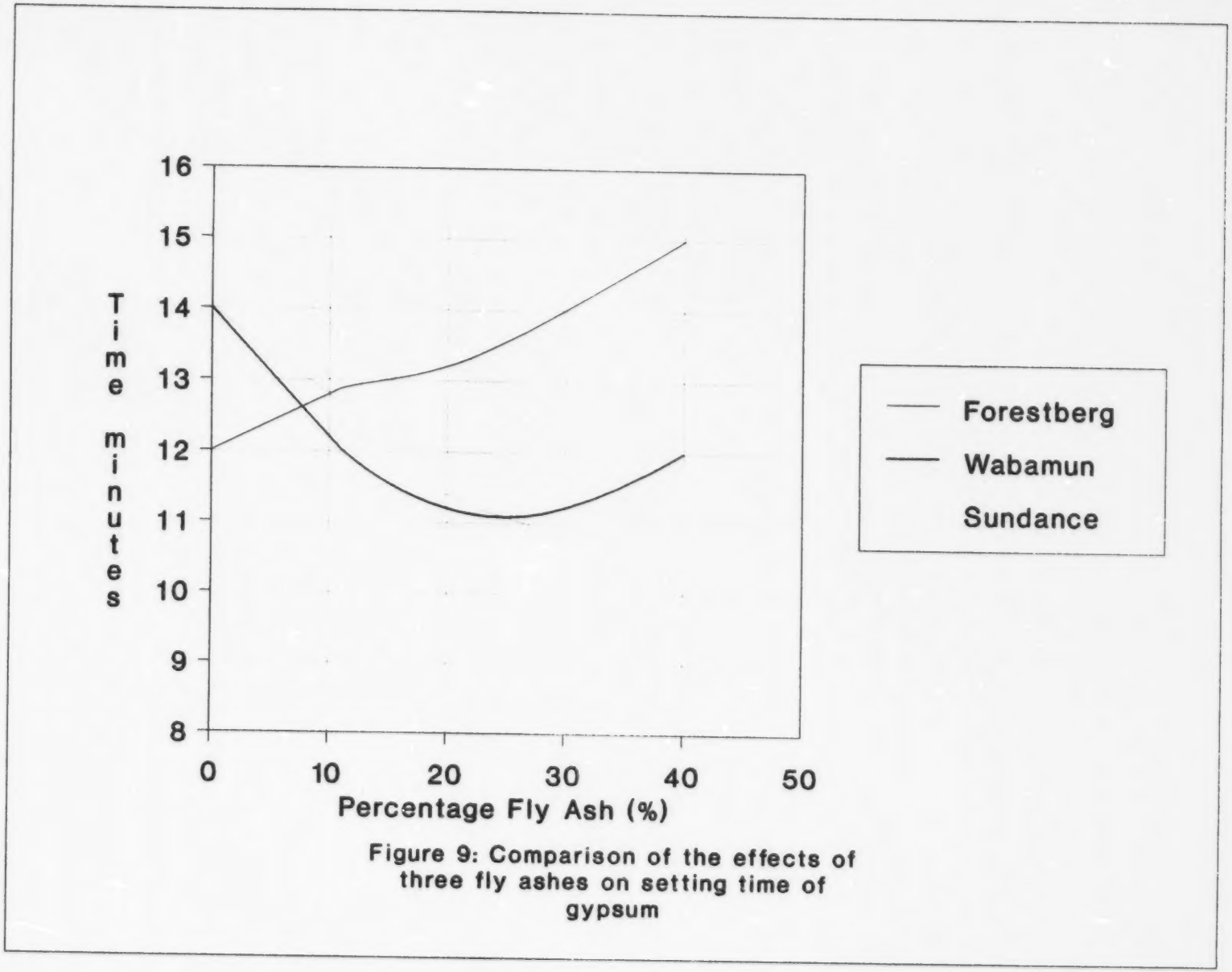


Figure 9: Comparison of the effects of three fly ashes on setting time of gypsum

Table 13

SETTING TIMES
Forestberg Fly Ash

Percentage of Fly ash	Weight (g) Gypsum	Weight (g) Fly ash	Total Weight	Water/Stucco Ratio	Water (ml)	Setting Time (min)
0	200	0	200	0.70	140	12
10	180	20	200	0.65	130	13
20	160	40	200	0.60	120	13
30	140	60	200	0.55	110	14
40	120	80	200	0.53	106	15

Table 14

SETTING TIMES
Wabamun Fly Ash

Percentage of Fly ash	Weight (g) Gypsum	Weight (g) Fly ash	Total Weight	Water/Stucco Ratio	Water (ml)	Setting Time (min)
0	200	0	200	0.65	130	14
10	180	20	200	0.65	130	12
20	160	40	200	0.63	126	11
30	140	60	200	0.58	116	11
40	120	80	200	0.58	116	12

Table 15
SETTING TIMES
Sundance Fly Ash

Percentage of Fly ash	Weight (g) Gypsum	Fly ash	Total Weight	Water/Stucco Ratio	Water (ml)	Setting Time (min)
0	200	0	200	0.65	130	14
10	180	20	200	0.65	130	13
20	160	40	200	0.63	126	11
30	140	60	200	0.58	116	11
40	120	80	200	0.54	108	10

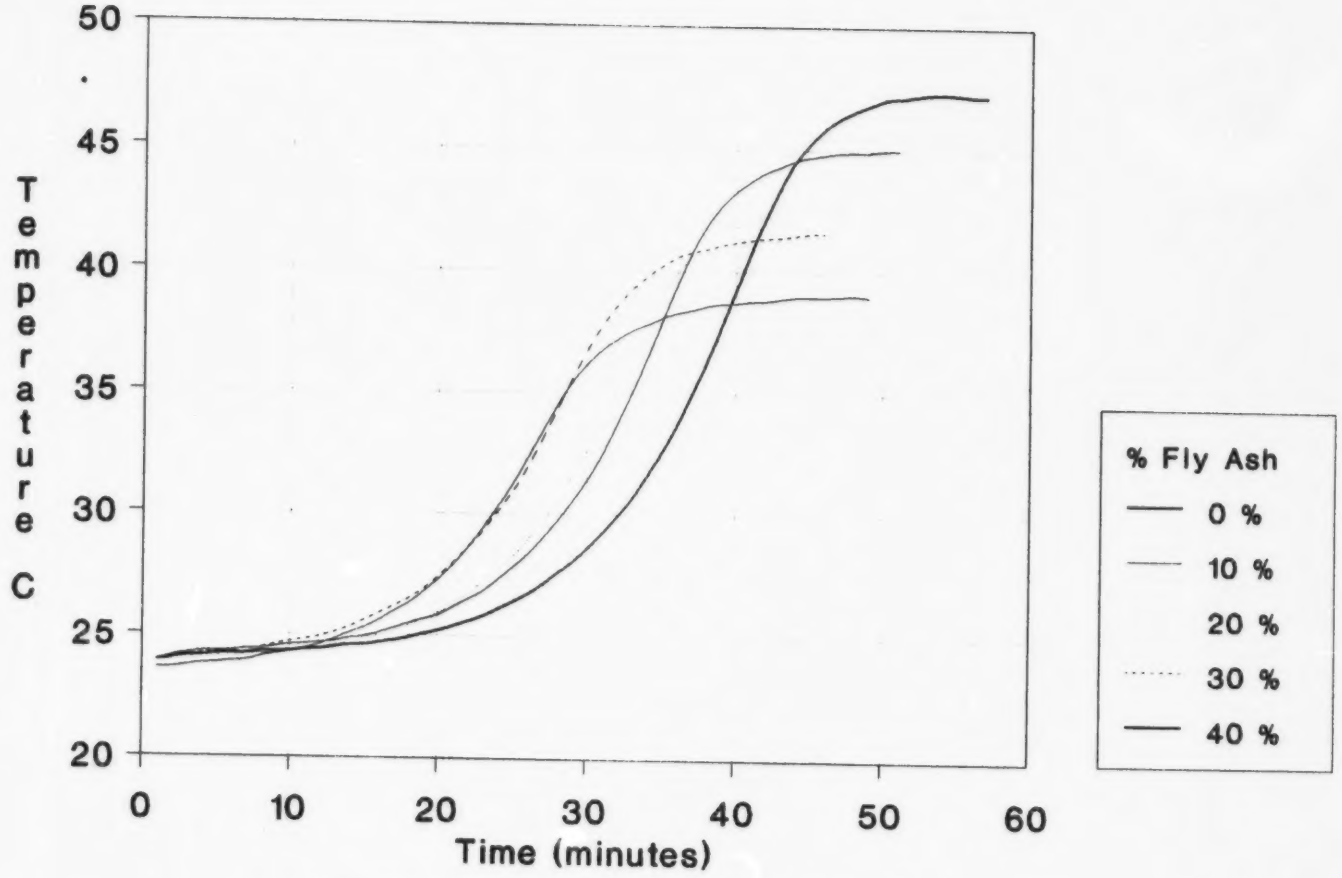


Figure 10: Temperature-Time relationship of Forestberg fly ash-Gypsum mixes

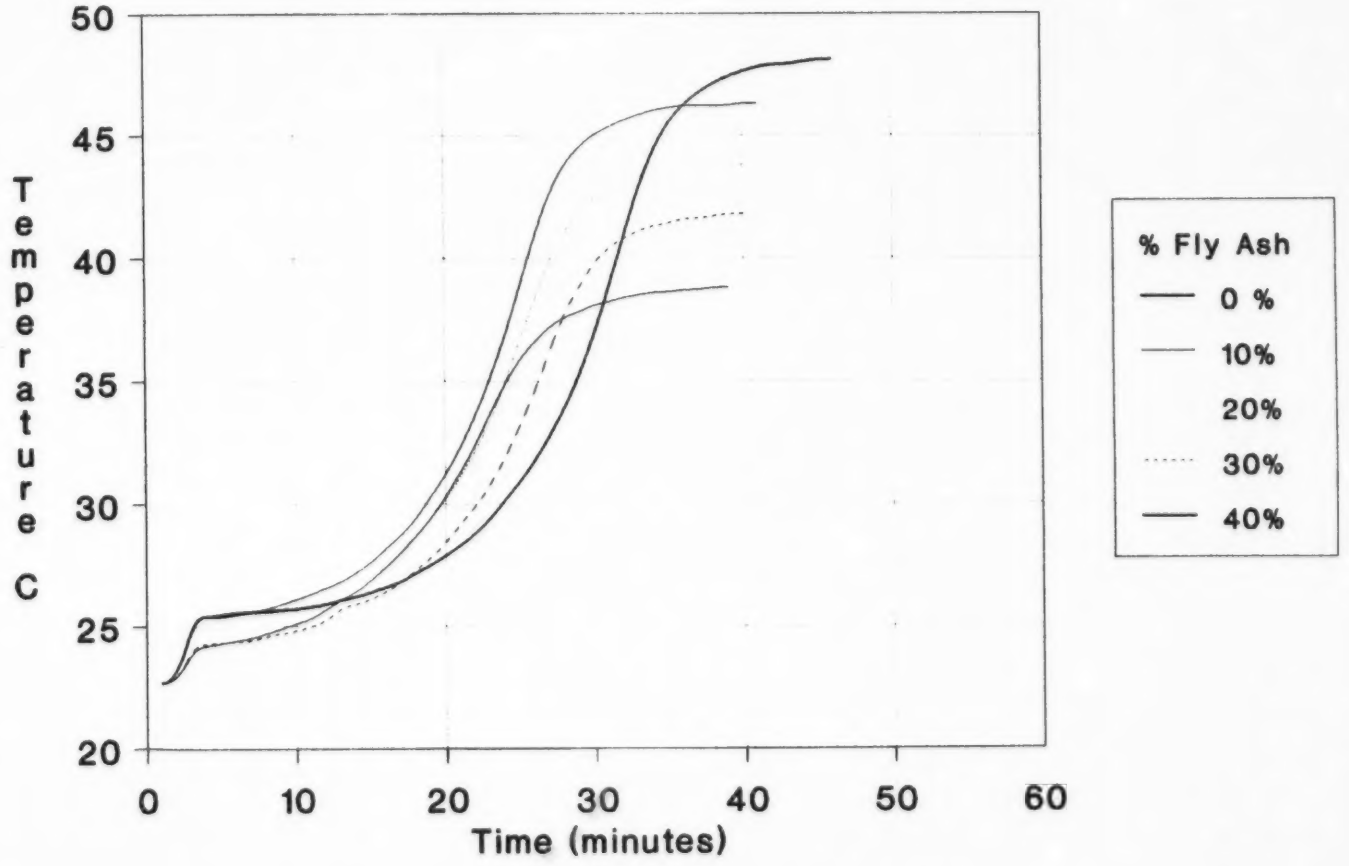


Figure 11:Temperature-Time relationship of Wabamun fly ash-Gypsum mixes

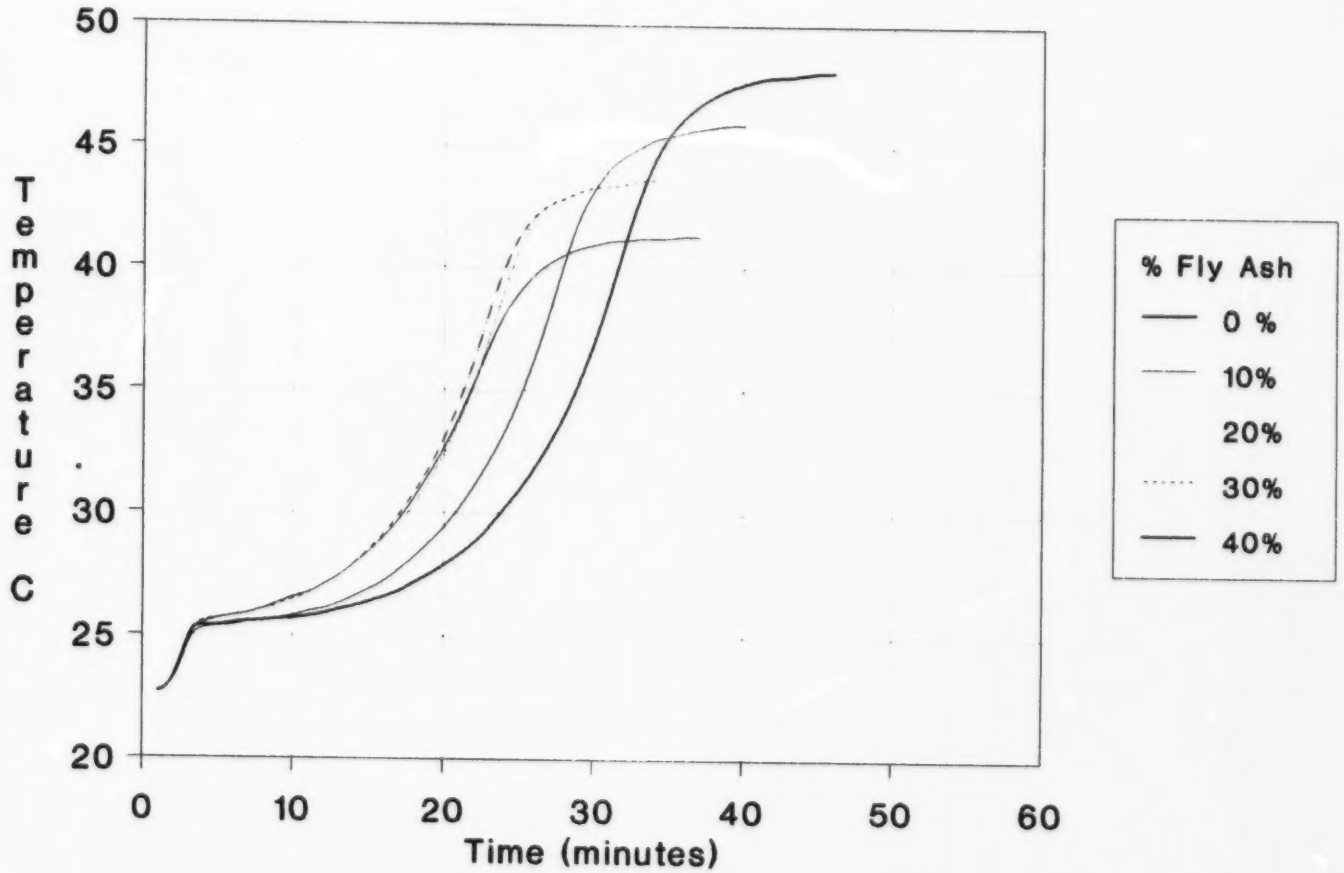


Figure 12; Temperature_Time relationship of Sundance fly ash- Gypsum mixes

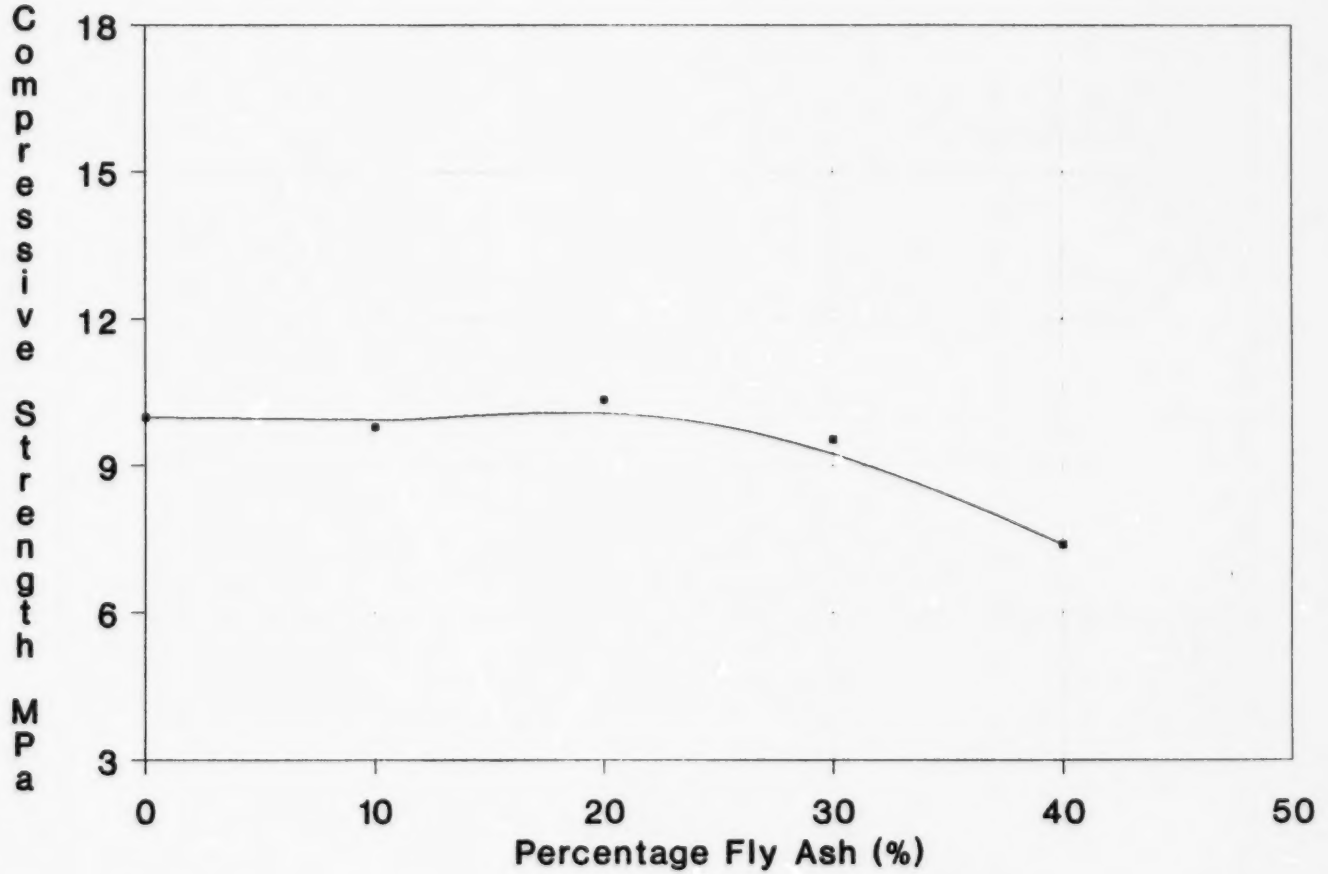


Figure 13:Compressive strength of 50 mm cubes of Gypsum-Forestberg fly ash mix

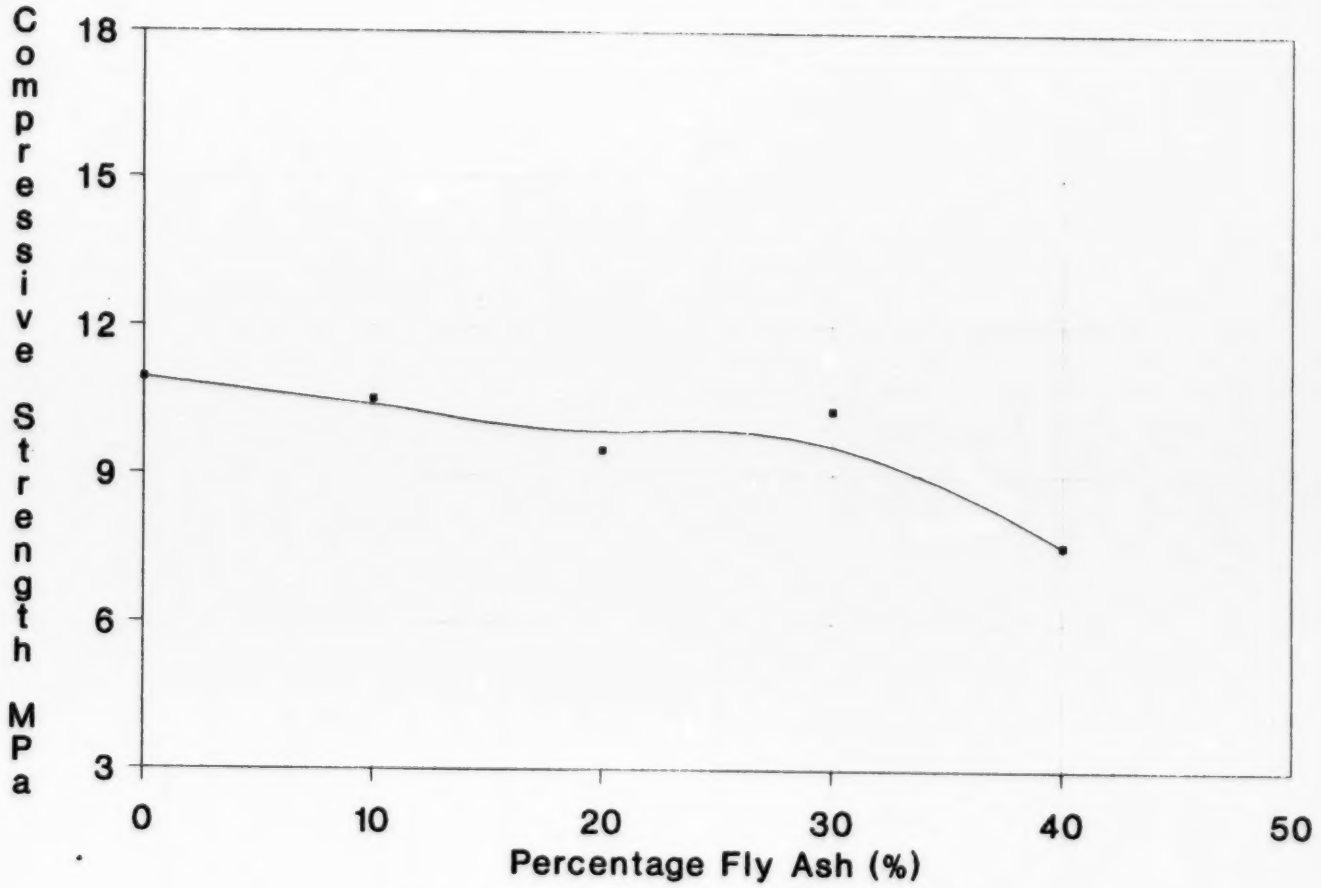


Figure 14: Compressive strength of 50 mm cubes of Gypsum-Wabamun fly ash mix

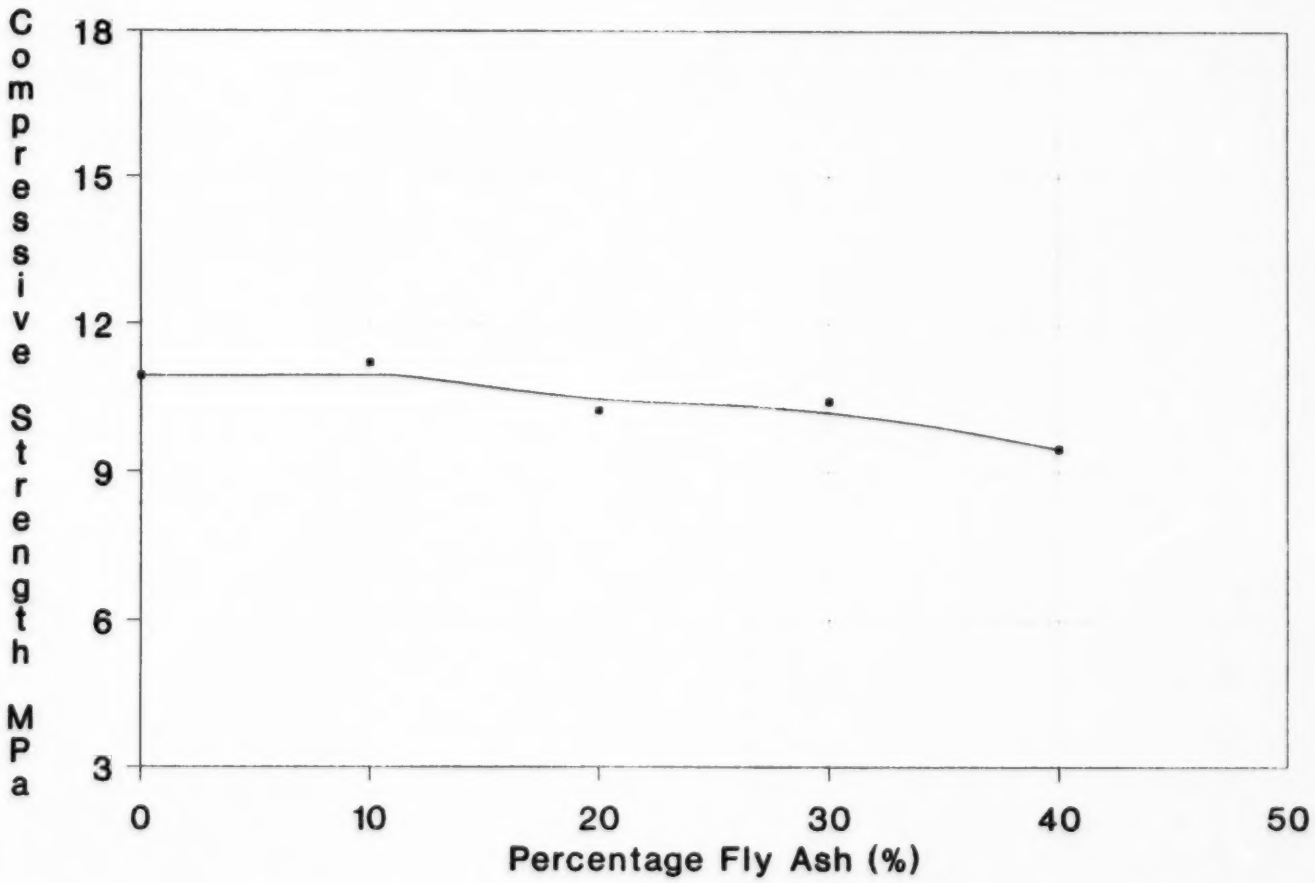


Figure 15: Compressive strength of 50 mm cubes of Gypsum-Sundance fly ash mix

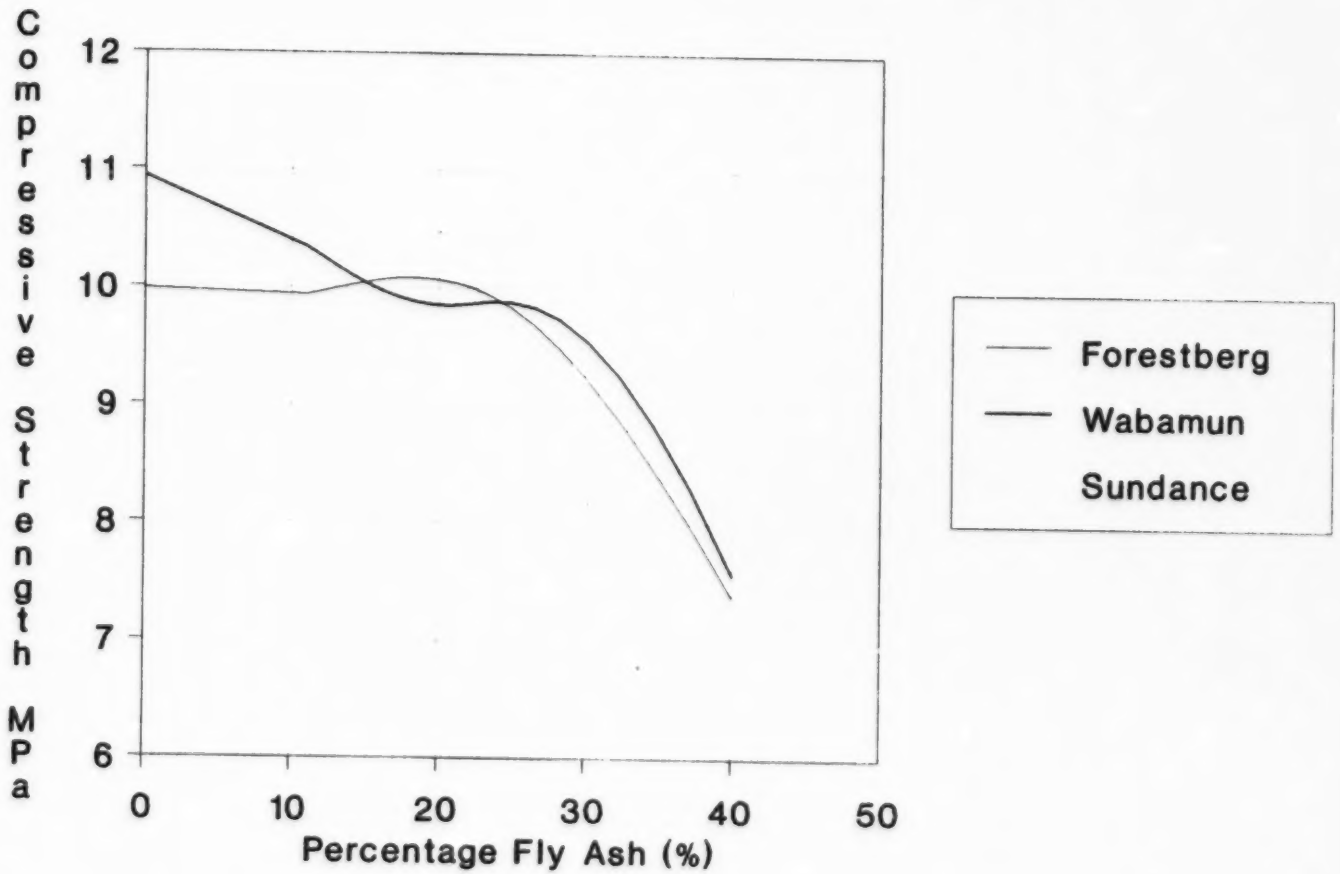


Figure 16: Comparison of the effects of three fly ashes on compressive strength of 50 mm cubes of gypsum-fly ash mix.

Table 16

COMPRESSIVE STRENGTH DATA
Forestberg Fly Ash

% Fly Ash	Failure Loads (lbs) 1	2	3	4	5	6	Average (lbs)	Strength Psi	MPa
0	5700	5960	4680	5710	5900	5690	5792	1448	9.98
10	5500	5930	5680	5600	5740	5620	5678	1420	9.79
20	5420	6260	6280	6000	6300	5720	5997	1500	10.34
30	5880	5180	4920	5480	5750	5980	5532	1383	9.54
40	3780	4000	4000	4540	4230	5140	4282	1071	7.38

Table 17

COMPRESSIVE STRENGTH DATA
Wabamun Fly Ash

% Fly Ash	Failure Loads (lbs) 1	2	3	4	5	6	Average (lbs)	Strength Psi	MPa
0	6790	6240	6440	6120	6120	5060	6342	1586	10.94
10	4640	6240	6240	6040	6020	5980	6104	1526	10.52
20	5140	5700	5700	5830	5270	5340	5497	1375	9.48
30	6200	6260	5880	5730	5860	5820	5959	1490	10.27
40	5000	4440	4200	4400	4460	4460	4392	1098	7.57

Table 18

COMPRESSIVE STRENGTH DATA
Sundance Fly Ash
Failure Loads (lbs)

% Fly Ash	1	2	3	4	5	6	Average (lbs)	Strength Psi	Strength MPa
0	6790	6240	6440	6120	6120	5060	6342	1586	10.94
10	6760	6510	6460	6200	6490	6560	6497	1625	11.20
20	6100	6190	6180	5800	5700	5660	5939	1485	10.24
30	6300	6270	6160	5820	5840	5860	6042	1511	10.42
40	5710	5800	5600	5580	5140	5100	5489	1373	9.47

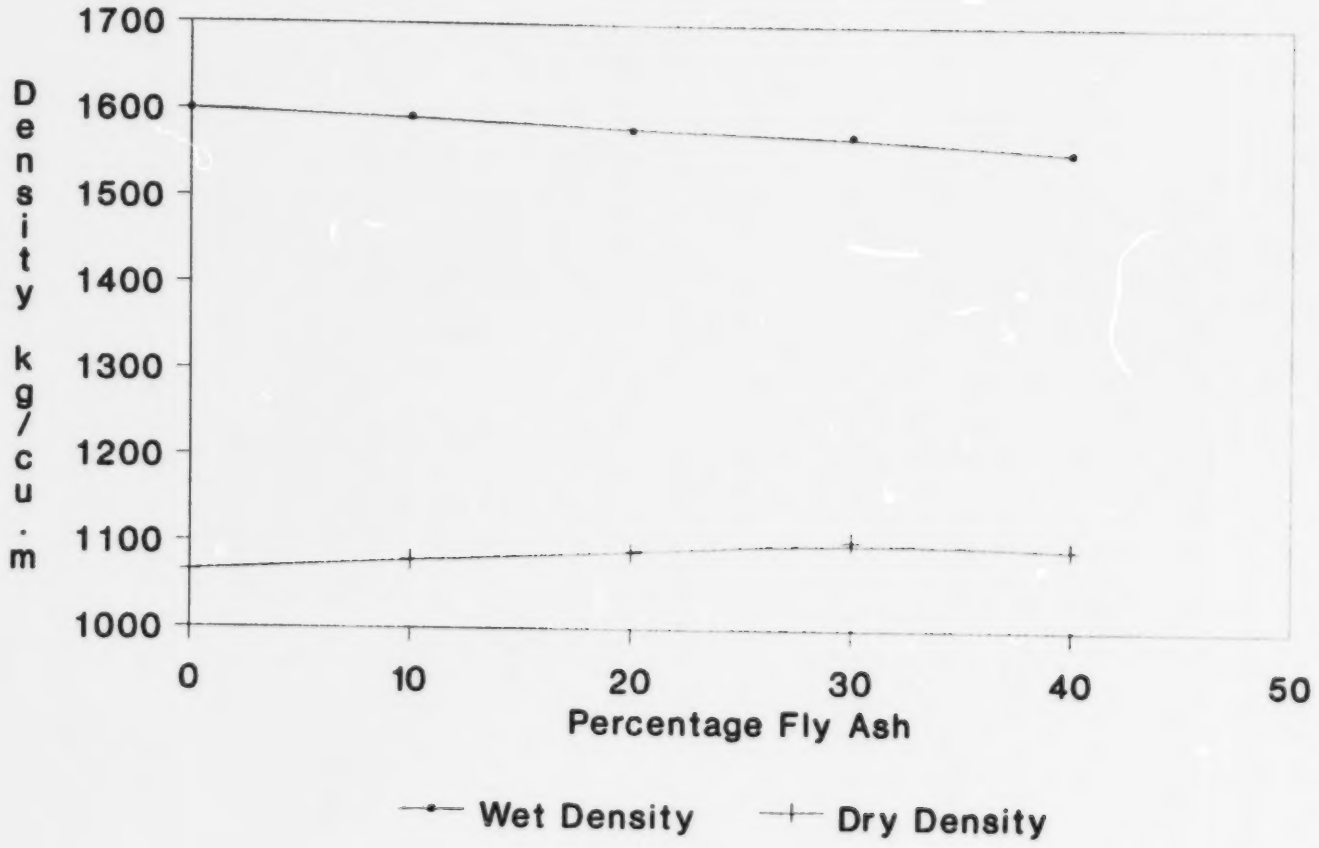


Figure 17; Density of Gypsum-Forestberg fly ash mixes.

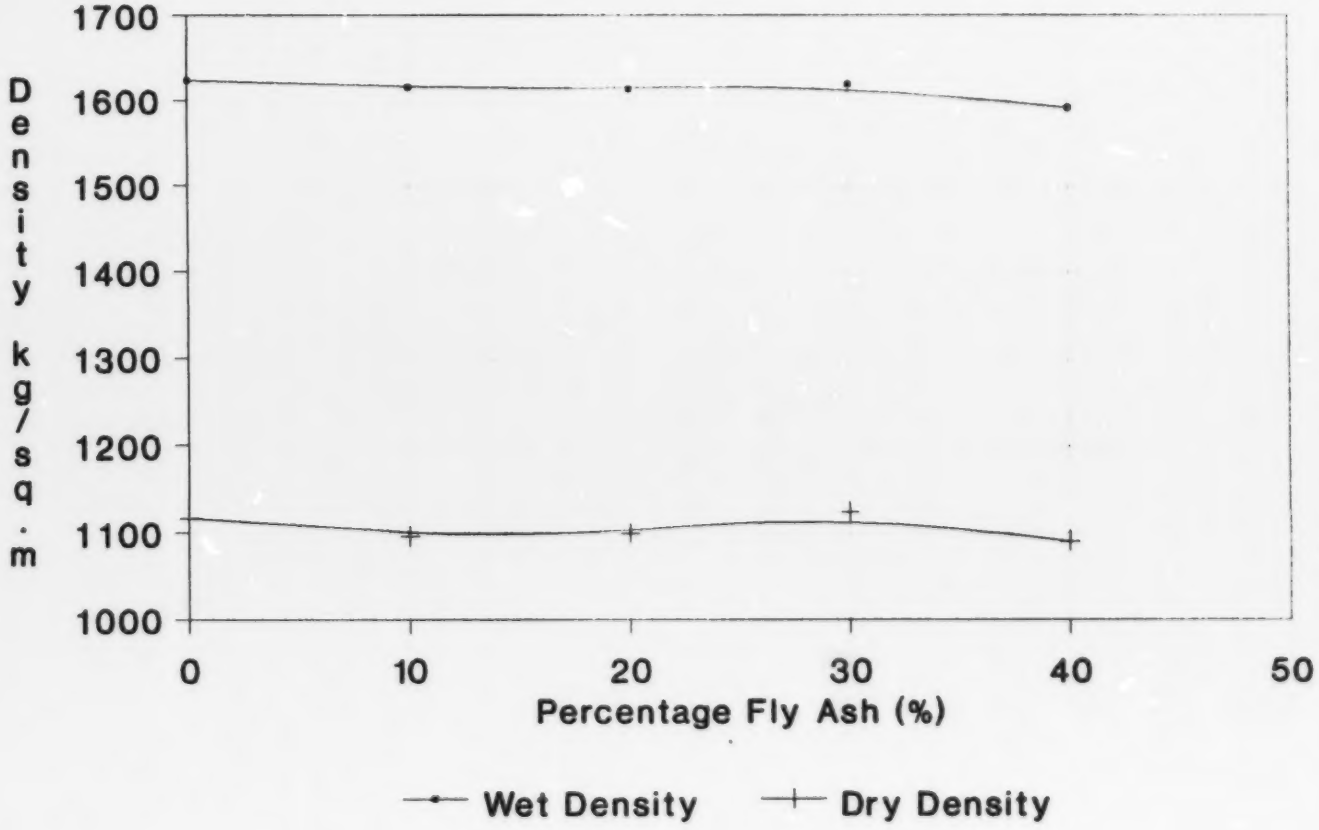


Figure 18: Density of Gypsum-Wabamun fly ash mixes.

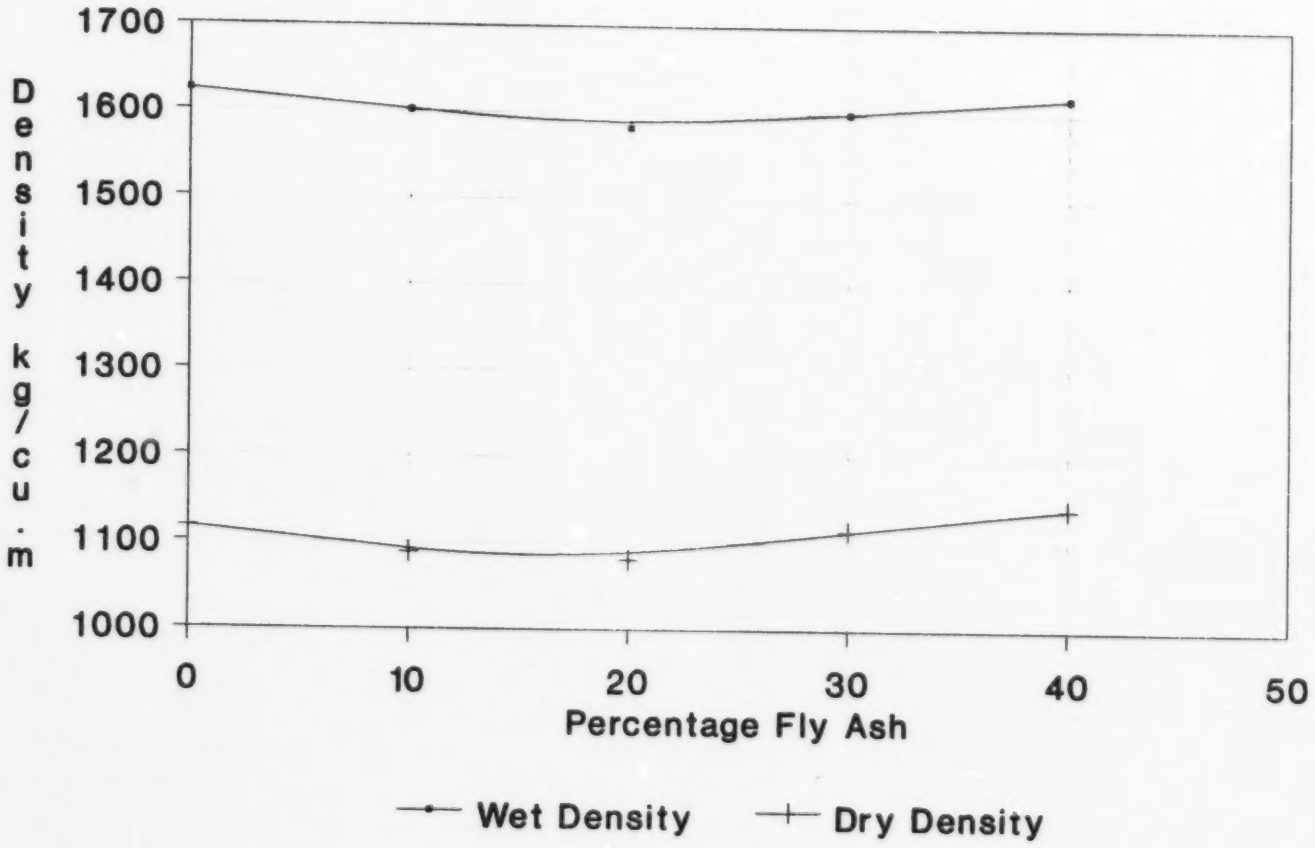


Figure 19: Density of Gypsum-Sundance fly ash mixes

Table 19

INDIVIDUAL CUBE MASS DATA
Forestberg Fly Ash

% Fly Ash		Mass (g) 1	2	3	4	5	6	Total Mass (g)
0	w	207.9	211.5	209.7	209.0	210.5	209.7	1258.3
	d	140.0	140.6	139.3	139.1	139.8	139.5	838.3
10	w	208.3	209.6	207.5	208.6	209.5	208.6	1252.1
	d	140.9	141.7	140.5	141.2	142.1	141.3	847.7
20	w	206.6	207.5	207.8	205.9	207.1	206.6	1241.5
	d	142.3	142.8	143.1	142.2	142.9	142.3	855.6
30	w	206.6	206.9	204.3	205.8	206.6	206.5	1236.7
	d	144.7	144.9	142.6	144.4	145.0	145.1	866.7
40	w	201.7	203.1	202.8	203.9	205.8	205.6	1222.5
	d	141.5	142.3	142.4	143.6	144.9	145.0	859.7

w=wet wt, d=dry wt.

Table 20
INDIVIDUAL CUBE MASS DATA
Wabamun Fly Ash

% Fly Ash		Mass (g) 1	2	3	4	5	6	Total Mass (g)
0	w	213.5	213.2	213.2	213.1	213.2	210.5	1276.7
	d	147.8	146.7	147.8	146.7	146.6	142.0	877.6
10	w	211.5	211.8	211.3	212.3	211.6	211.8	1270.3
	d	143.7	143.9	143.6	144.0	143.6	143.4	862.2
20	w	212.2	211.6	211.2	212.0	210.6	211.0	1268.6
	d	144.5	144.3	143.9	144.3	143.5	143.9	864.4
30	w	212.8	212.4	213.3	212.1	211.2	211.7	1273.5
	d	147.7	147.5	148.2	147.0	146.5	146.9	883.8
40	w	208.7	208.1	207.6	208.1	209.3	209.7	1251.5
	d	142.9	142.6	142.2	142.7	143.4	143.8	857.6

w=wet wt, d=dry wt.

Table 21

INDIVIDUAL CUBE MASS DATA
Sundance Fly Ash

% Fly Ash		Mass (g) 1	2	3	4	5	6	Total Mass (g)
0	w	213.5	213.2	213.2	213.1	213.2	210.5	1276.7
	d	147.8	146.7	147.8	146.7	146.6	142.0	877.6
10	w	210.1	209.1	209.5	209.3	210.7	210.3	1259.0
	d	142.8	142.0	142.6	142.3	143.1	142.7	855.5
20	w	209.4	207.7	207.4	205.7	207.0	207.2	1244.4
	d	142.8	142.2	142.1	140.3	140.6	141.2	849.2
30	w	209.6	208.8	210.4	210.3	210.0	209.7	1258.8
	d	145.8	146.3	146.7	145.9	146.0	145.6	876.3
40	w	210.8	209.2	209.5	215.0	215.3	213.2	1273.0
	d	148.8	147.6	147.6	151.2	151.6	150.1	896.9

w=wet wt, d=dry wt.

Table 22

DENSITY CALCULATIONS
Forestberg Fly Ash

% Fly Ash	Total Wet Mass of 6 Cubes (g)	Total Dry Mass of 6 Cubes (g)	Density Wet lb/cu.	Wet kg/cu.m	Dry lb/cu.f	Dry kg/ cu.m
0	1258.3	838.3	99.86	1600	66.53	1066
10	1252.1	847.7	99.37	1592	67.28	1078
20	1241.5	855.6	98.53	1578	67.90	1088
30	1236.7	866.7	98.15	1572	68.79	1102
40	1222.5	859.7	97.02	1554	68.23	1093

Table 23
DENSITY CALCULATIONS
Wabamun Fly Ash

% Fly Ash	Total Wet Mass of 6 Cubes (g)	Total Dry Mass of 6 Cubes (g)	Density Wet lb/cu.	kg/cu.m	Dry lb/cu.f	kg/ cu.m
0	1276.7	877.6	101.32	1623	69.65	1116
10	1270.3	862.2	100.82	1615	68.43	1096
20	1268.6	864.4	100.68	1613	68.60	1099
30	1273.7	883.8	101.07	1619	70.14	1124
40	1251.5	857.6	99.32	1591	68.06	1090

Table 24

DENSITY CALCULATIONS
Sundance Fly Ash

% Fly Ash	Total Wet Mass of 6 Cubes (g)	Total Dry Mass of 6 Cubes (g)	Density			
			Wet		Dry	
			lb/cu.	kg/cu.m	lb/cu.f	kg/ cu.m
0	1276.7	877.6	101.32	1623	69.65	1116
10	1259.0	855.5	99.92	1601	67.90	1088
20	1244.4	849.2	98.76	1582	67.40	1080
30	1258.8	876.3	99.90	1577	69.55	1114
40	1273.0	896.9	101.03	1618	71.18	1095

Table 25

LONG-TERM TEST DATA-WITHOUT FLY ASH
Absorption of 2" cube specimens

Age (days)	Initial Weight	Dry wt. (A)	Weights after.. (B)					Absorption (%) [(B-A/A)x100]				
			1 hr.	2 hrs.	3hrs.	4 hrs.	24 hrs.	1 hr.	2 hrs.	3 hrs.	4 hrs.	24 hrs.
1	213.0	145.4	191.4	191.8	192.2	192.0	193.0	31.6	31.9	32.2	32.1	32.7
3	213.0	146.1	192.4	192.3	192.3	192.3	192.9	31.7	31.6	31.6	31.6	32.0
7	213.1	145.5	192.4	192.8	192.9	192.9	193.2	32.2	32.5	32.6	32.6	32.8
28	216.6	140.9	184.1	184.2	184.8	184.8	185.2	30.7	30.7	31.2	31.2	31.4
56	215.1	144.1	190.1	191.3	191.5	191.3	191.3	31.9	32.8	32.9	32.8	32.8
180.0	214.2	147.1	195.8	196.1	196.7	196.7	197.0	33.1	33.3	33.7	33.7	33.9

Table 26

LONG-TERM TEST DATA-30% SUNDANCE FLY ASH
Absorption of 50 mm cube specimens

Age (days)	Initial Weight	Dry wt. (A)	Weights after.. (B)					Absorption (%) [(B-A/A)x100]				
			1 hr.	2 hrs.	3hrs.	4 hrs.	24 hrs.	1 hr.	2 hrs.	3 hrs.	4 hrs.	24 hrs.
1	213.0	148.1	195.5	196.0	196.0	196.0	197.0	32.0	32.3	32.3	32.3	33.0
3	211.0	146.4	194.4	194.5	194.9	194.9	195.7	32.8	32.9	33.1	33.1	33.7
7	210.5	146.2	194.6	195.5	194.7	194.7	195.3	33.1	33.1	33.2	33.2	33.2
28	214.6	146.6	196.2	196.3	196.3	196.3	196.7	32.8	33.9	33.9	33.9	34.2
56	214.8	146.3	197.0	197.0	196.6	196.5	196.7	34.7	34.7	34.4	34.3	34.5
180.0	210.3	142.8	193.2	192.6	192.3	192.3	192.8	35.3	34.9	34.7	34.7	35.0

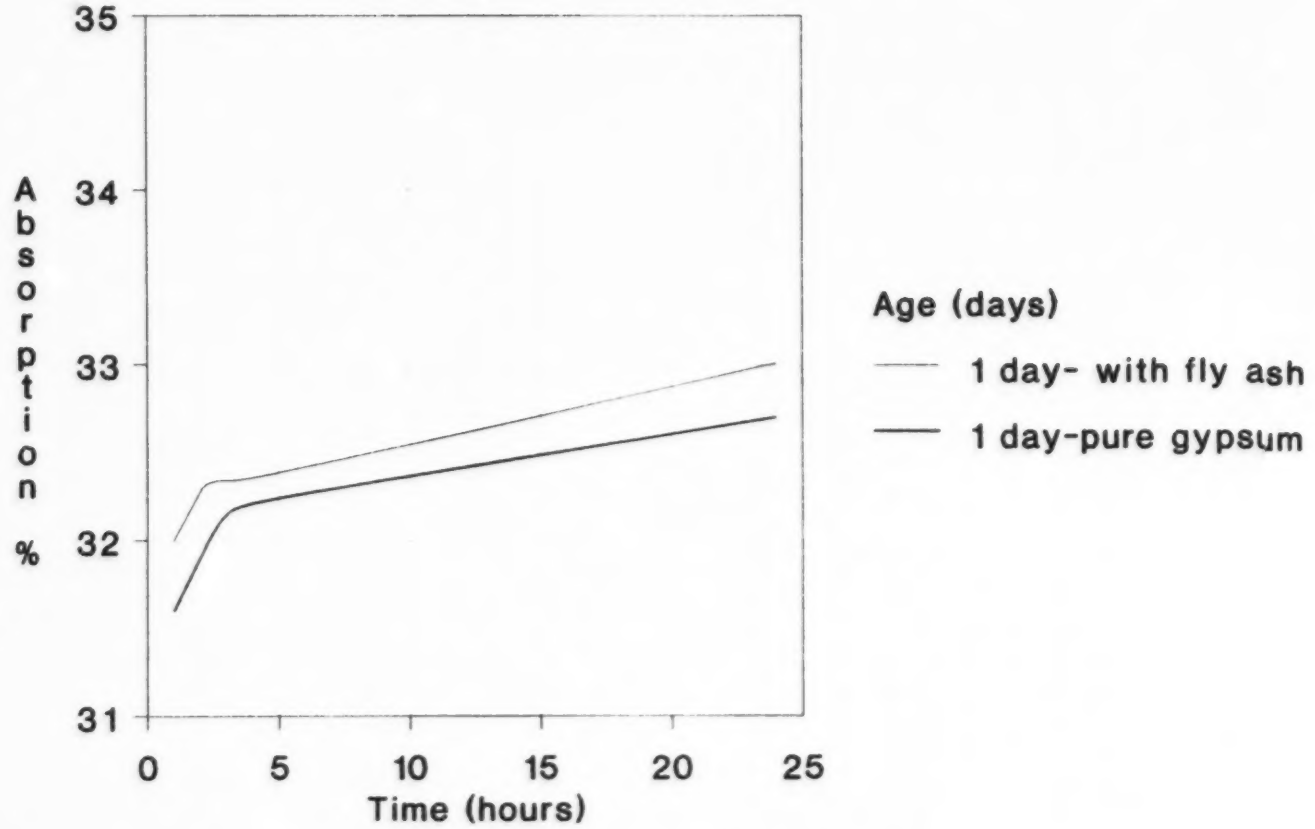


Figure 20: Water absorption of 50 mm gypsum cube specimens containing 30% Sundance fly ash and cured for one day.

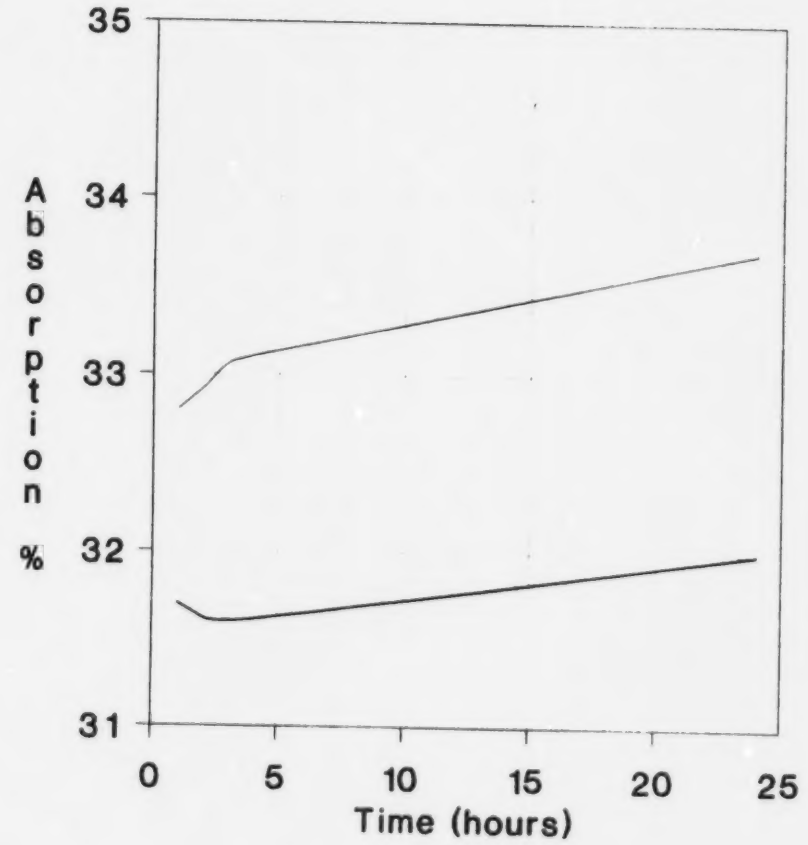


Figure 21: Water absorption of 50 mm gypsum cube specimens containing 30% Sundance fly ash and cured for 3 days.

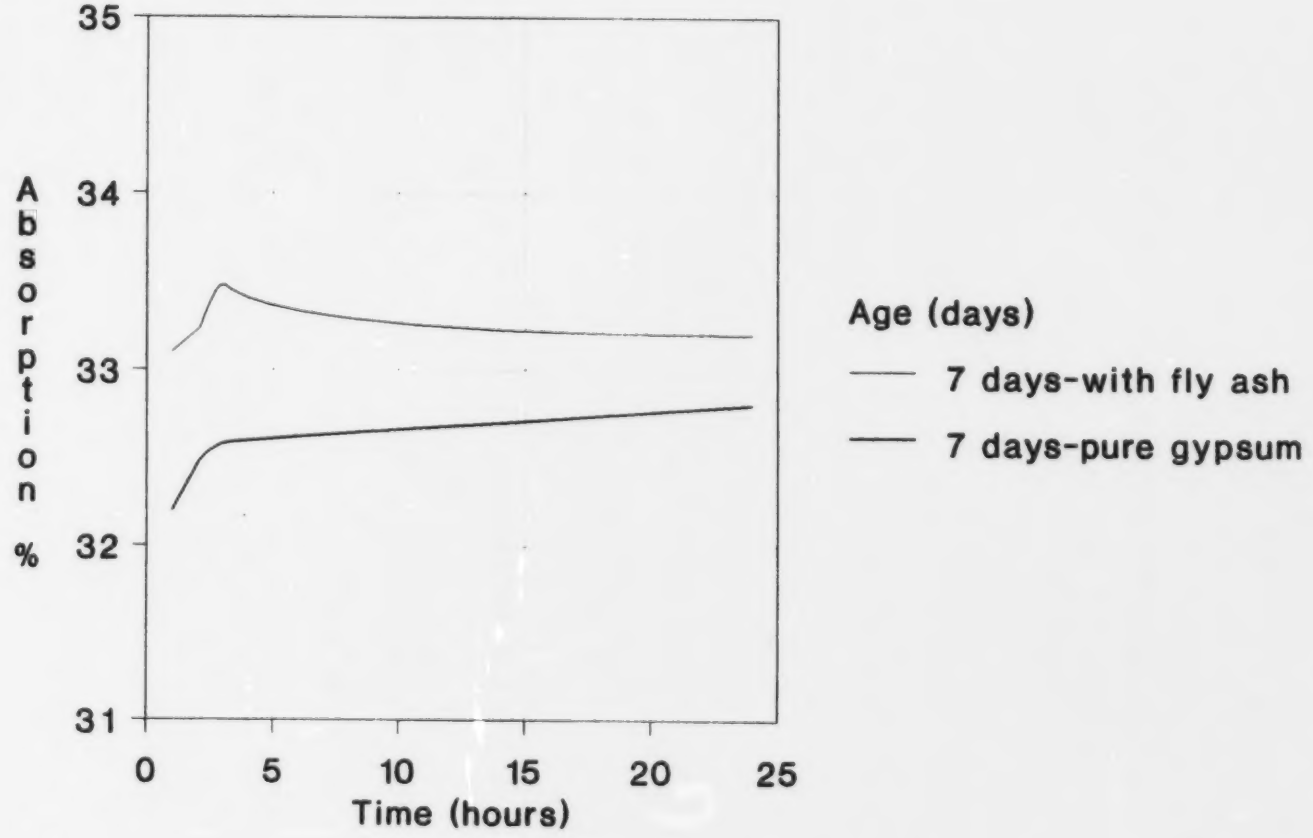


Figure 22: Water absorption of 50 mm gypsum cube specimens containing 30% Sundance fly ash and cured for 7 days.

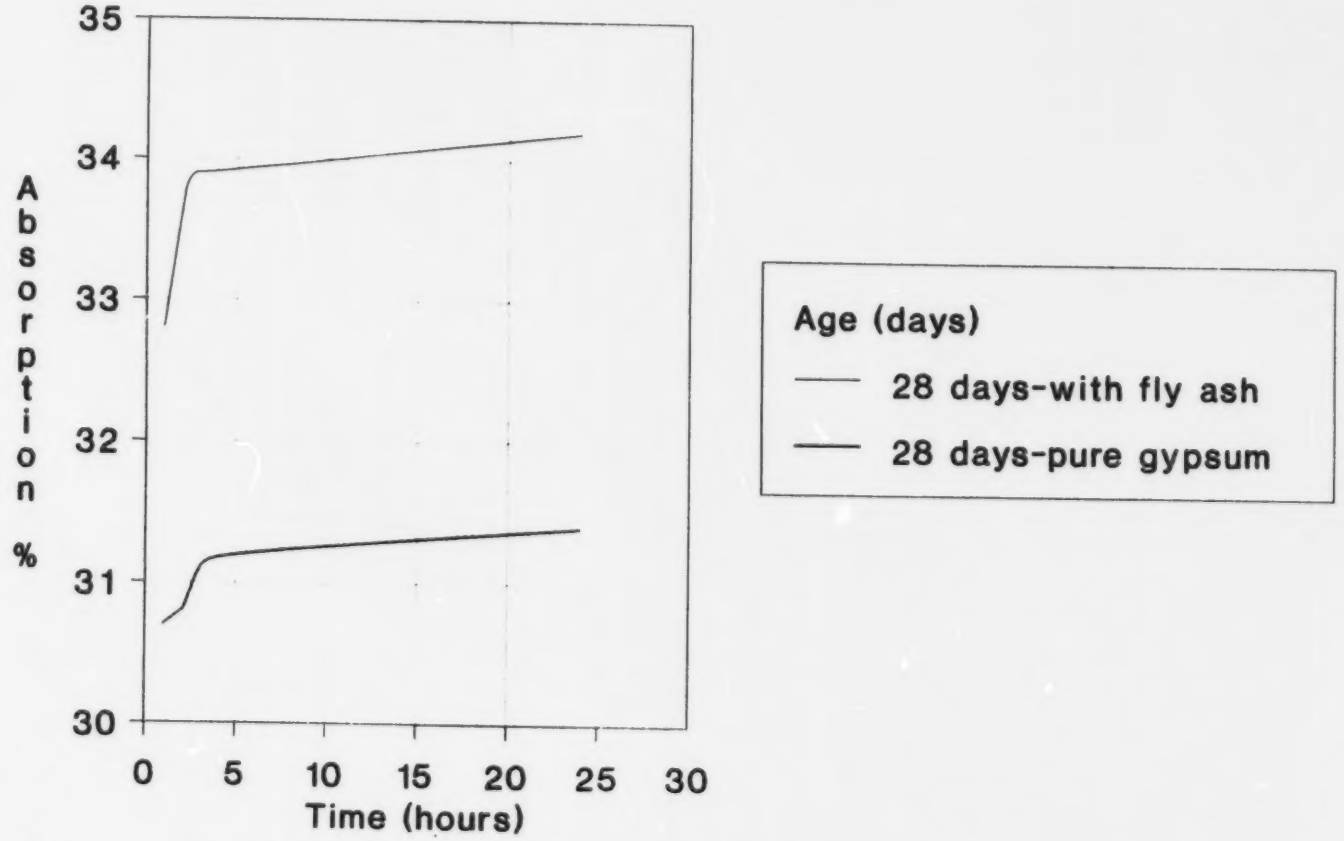


Figure 23: Water absorption of 50mm gypsum cube specimens containing 30% Sundance fly ash and cured for 28 days.

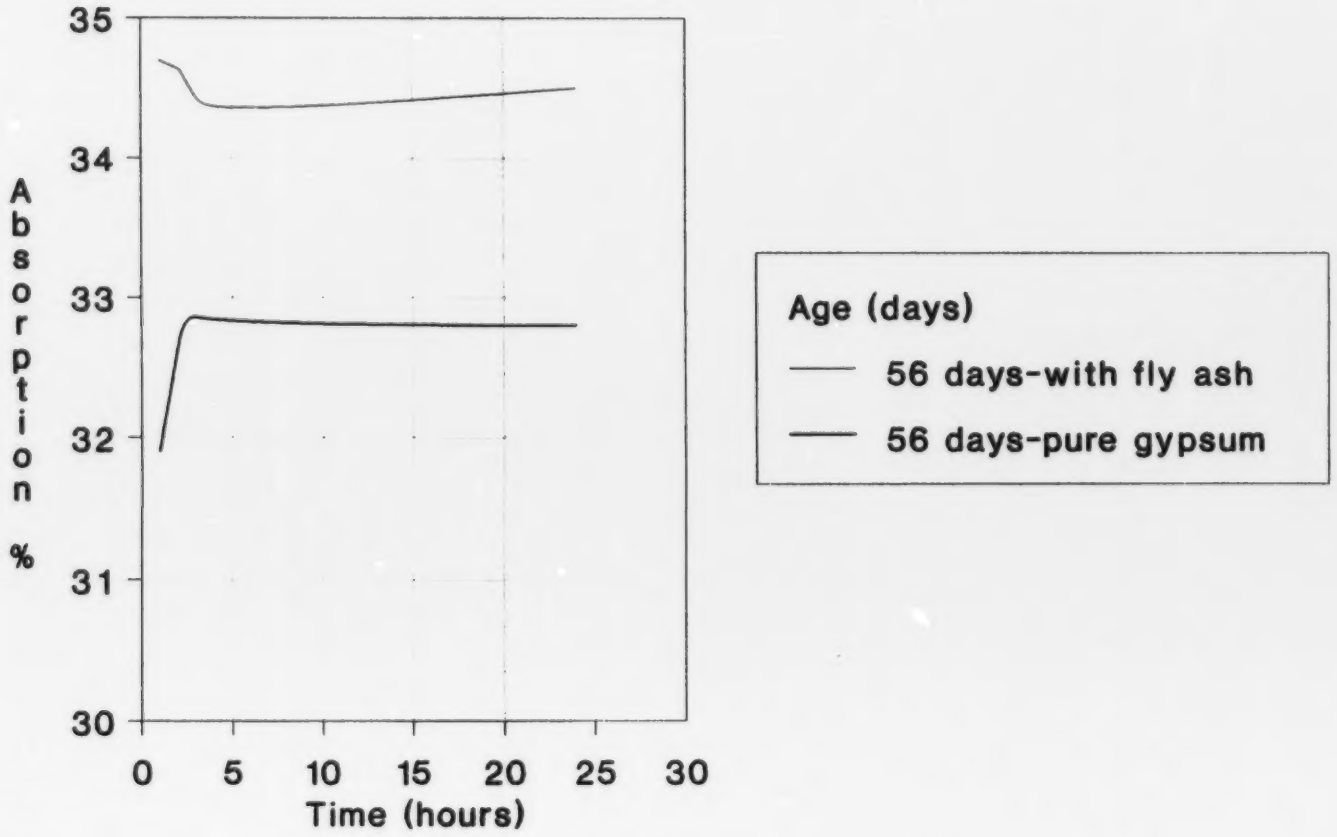


Figure 24: Water absorption of 50 mm gypsum cube specimens containing 30% Sundance fly ash and cured for 56 days.

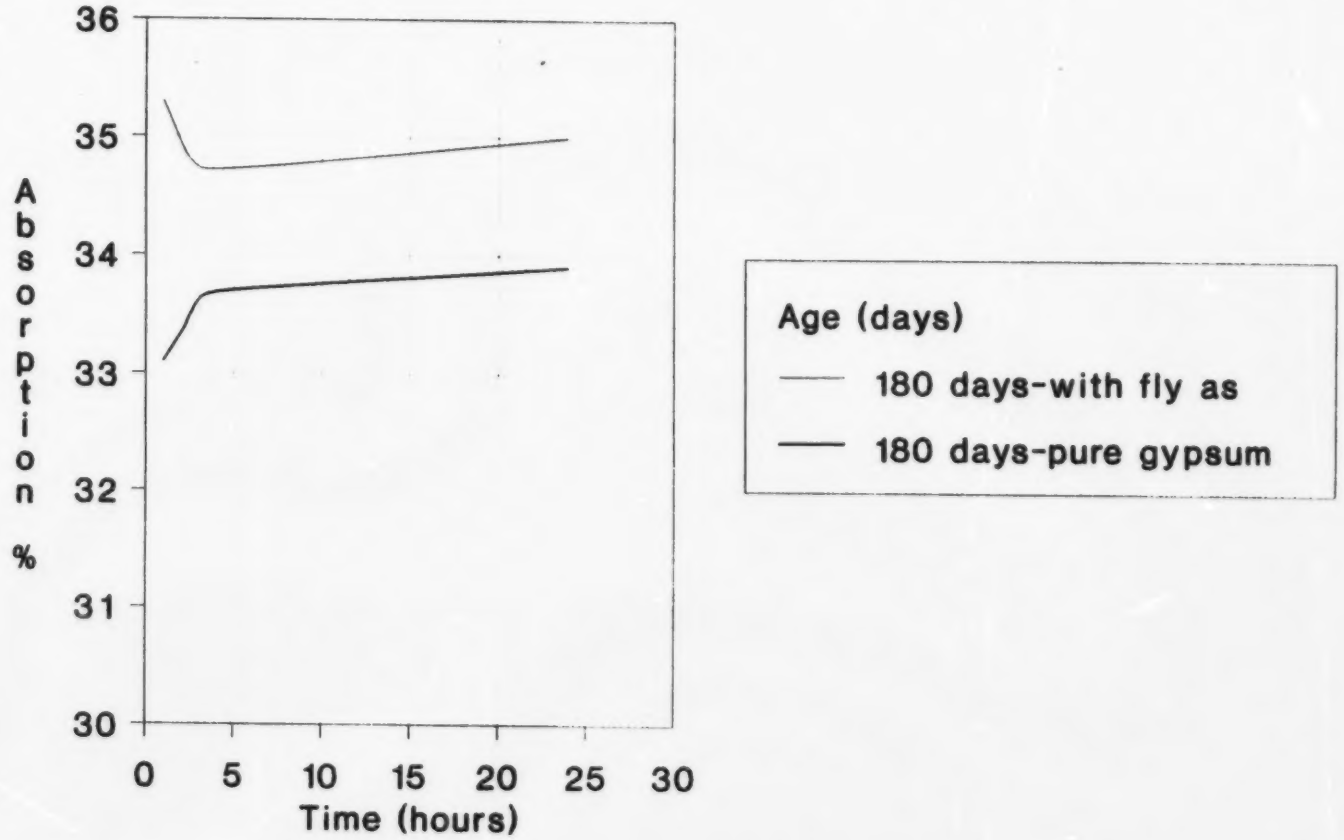


Figure 25: Water absorption of 50 mm gypsum cube specimens containing 30% Sundance fly ash and cured for 180 days.

Table 27

LONG-TERM TEST DATA-30% Sundance Fly Ash
Compressive strength of 2" cube specimens

Age (days)	Moist cured and oven dried specimen, failure load (lb) 1	2	3	Average (lb)	Compressive Strength Psi	MPa
1	5550	5230	4540	5390	1348	9.29
3	5800	5940	6000	5914	1479	10.20
7	4940	5740	6040	5890	1473	10.16
28	5350	6120	5880	6000	1500	10.34
56	5950	6140	5950	6014	1504	10.36
180	6240	6400	6080	6240	1560	10.76
			WITHOUT FLY ASH			
1	6120	6180	6180	6160	1540	10.62
3	6070	6270	6470	6270	1568	10.81
7	6700	6100	6025	6275	1569	10.82
28	6500	6680	6620	6600	1650	11.38
56	6520	6510	6500	6510	1628	11.23
180	6250	6430	6560	6414	1604	11.06

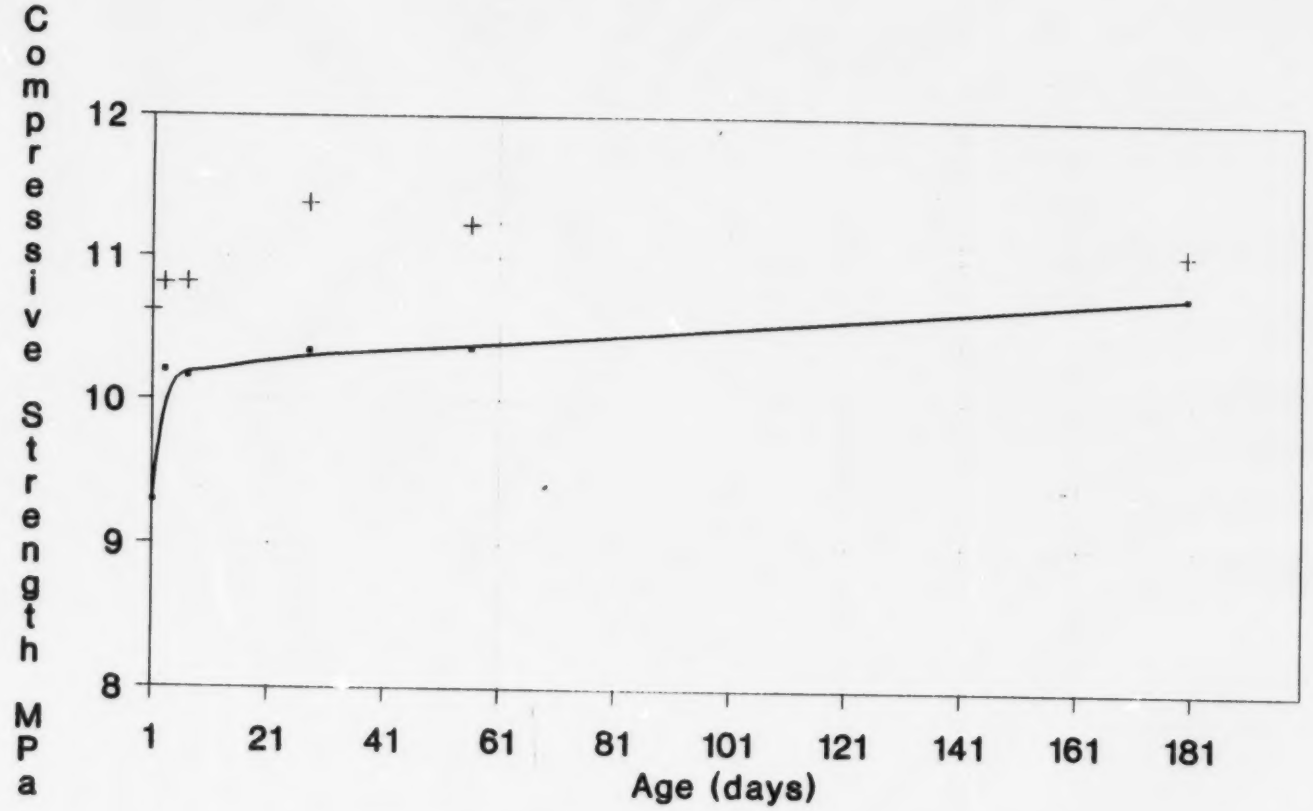
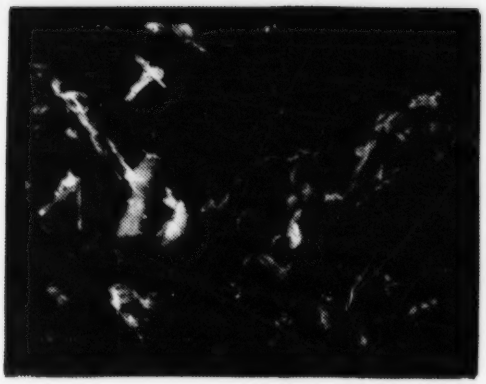


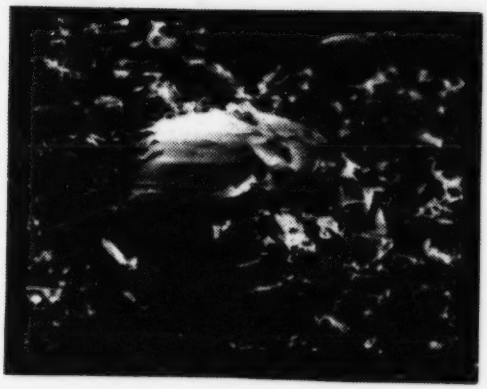
Figure 26: Compressive strength of 50 mm cubes containing gypsum-Sundance fly ash mix cured upto 180 days in the fog-room.

Figure 27



1

Micrographs



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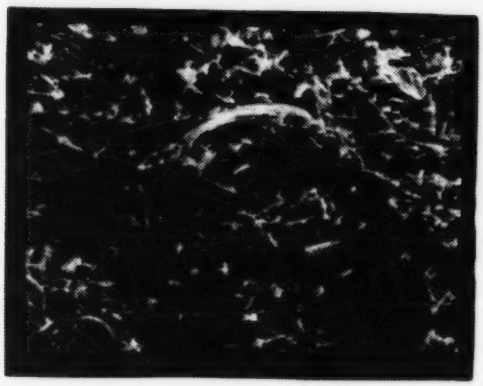

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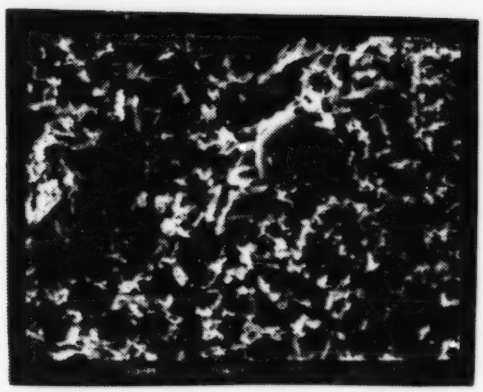

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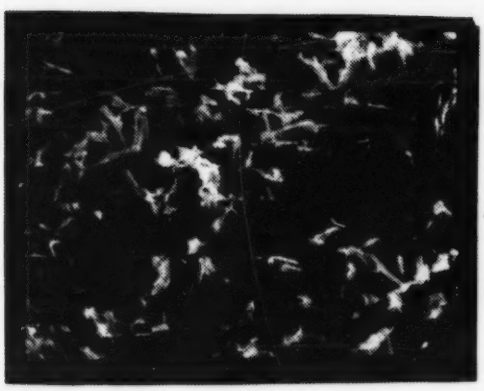

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APPENDIX C

Physical Testing of Wallboard Specimens Prepared in the Laboratory

APPENDIX C

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Figure 29 -	600 x 450 mm and 400 x 300 mm wallboard samples	C1
Figure 30 -	600 x 450 mm wallboard specimen	C2
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Figure 33 -	Humidified deflection test	C3
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Figure 35 -	Core hardness test (before nail is inserted)	C5
Figure 36 -	Core hardness test (after nail is inserted)	C5
Figure 37 -	Nailhead pull resistance test (before nail is inserted)	C6
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Figure 39 -	Thermal conductivity test	C7
Figure 40 -	Breaking strengths of cross grained wallboard specimens with and without fly ash	C13
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Table 33 -	Mass per unit area of wallboard specimens with and without fly ash	C12
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Table 36 -	Gas fired kettle operating data Source: Kelly, K.K., Southard, J.C., and Anderson, C.T., "Thermodynamic Properties of Gypsum and its Dehydration Products", U.S.D.I., Bureau of Mines, Technical Paper 625, Washington, D.C., 1941, pp. 62.	C20

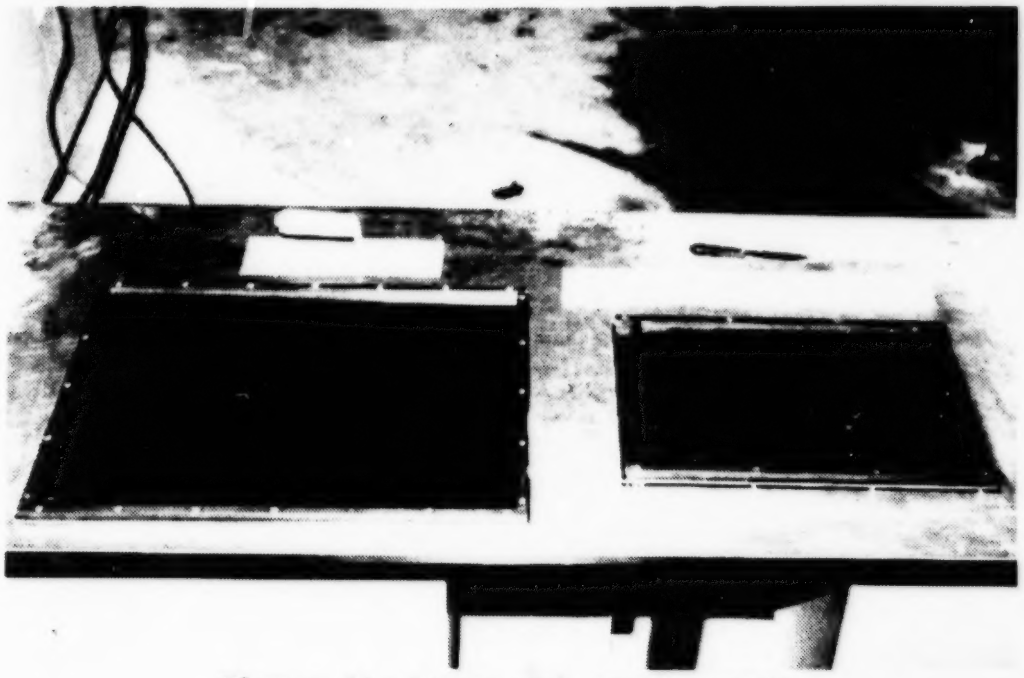

Figure 28- Large and small moulds

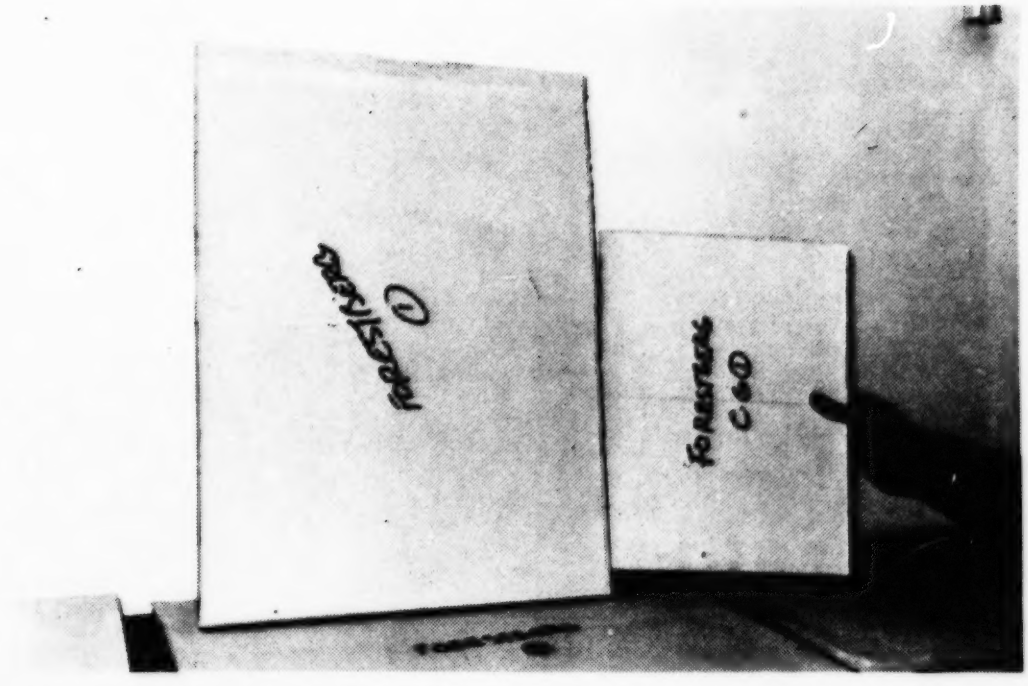

Figure 29- 600x450 mm and 400x300 mm wallboard specimens

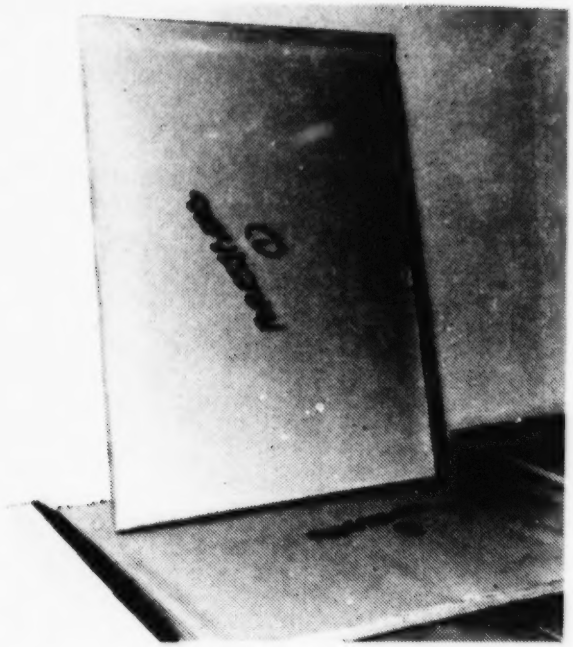

Figure 30- 600x450 mm wallboard specimen

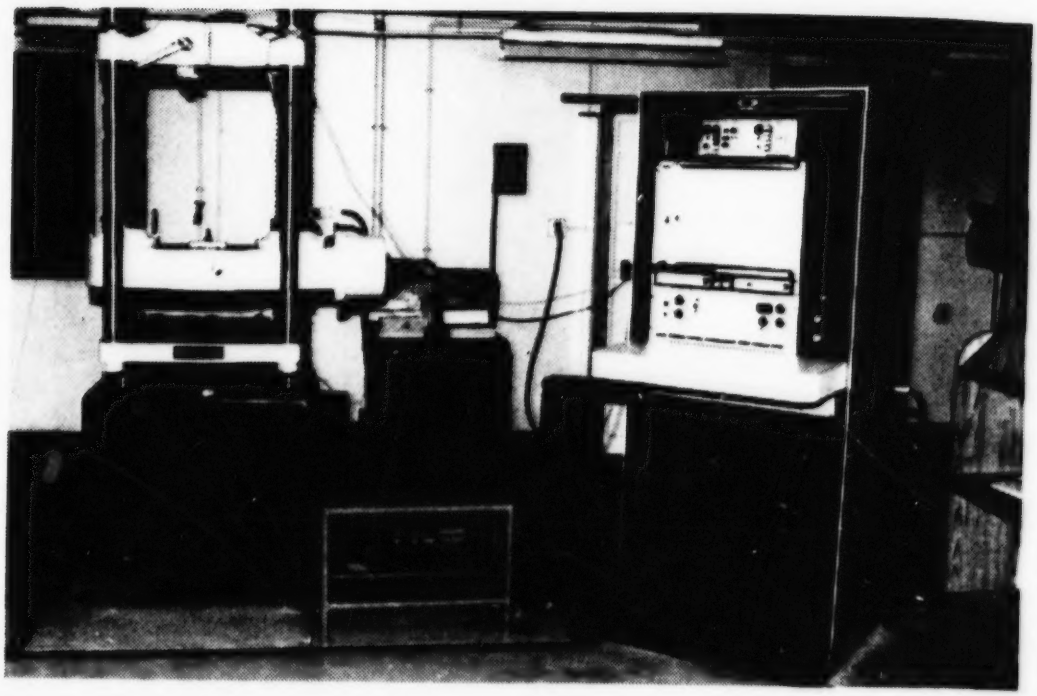

Figure 31- Testing Machine

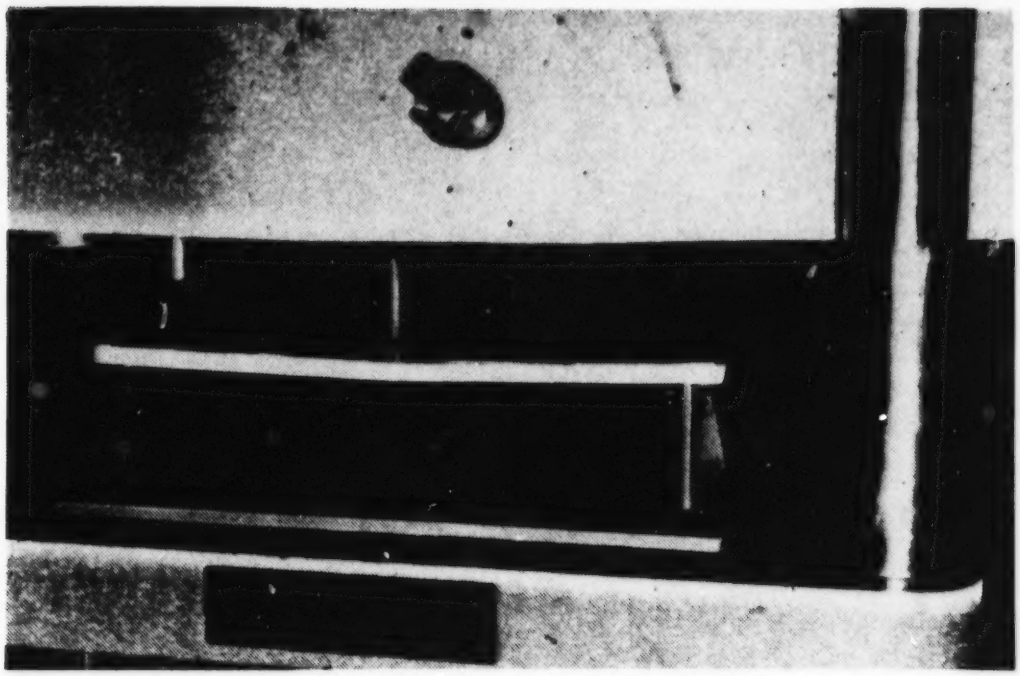

Figure 32- Breaking strength test setup

Figure 33- Humidified deflection test

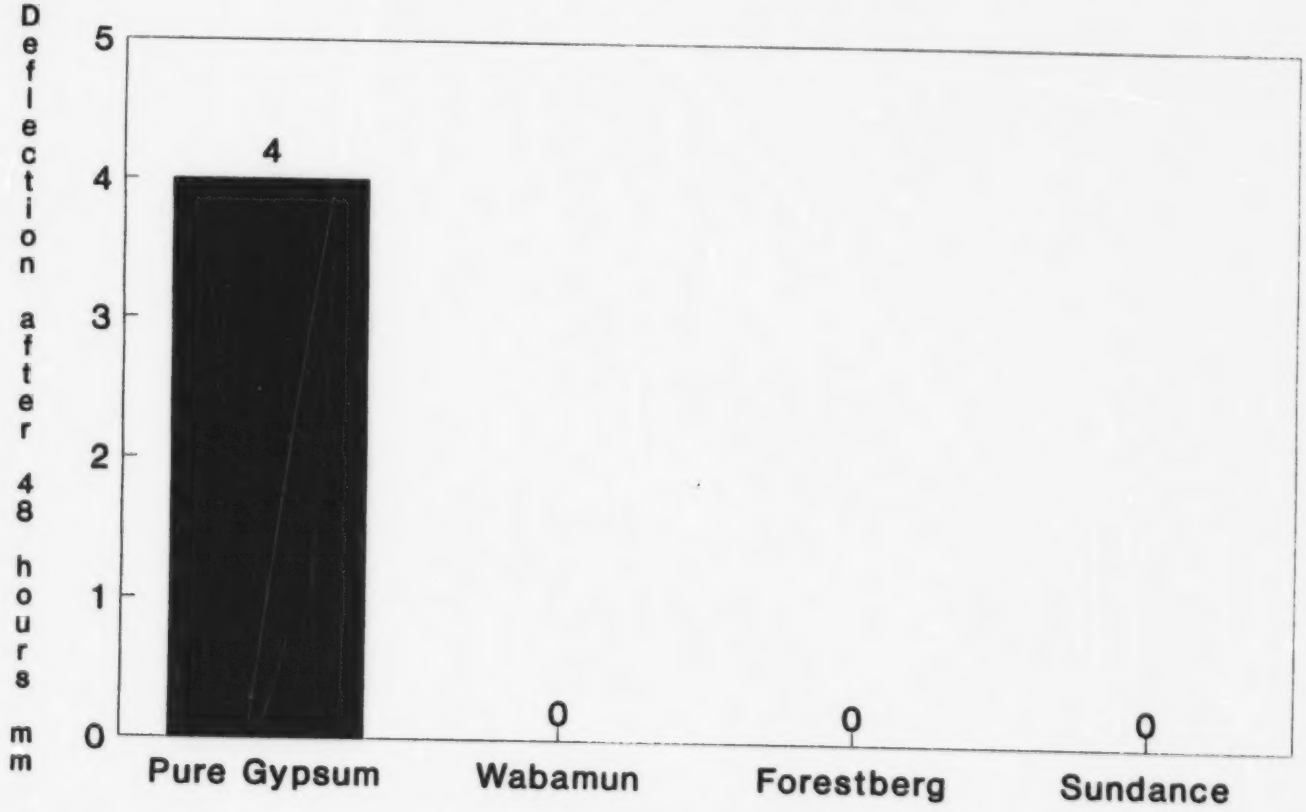

Figure 34: Humidified deflection of wallboard specimens with and without fly ash

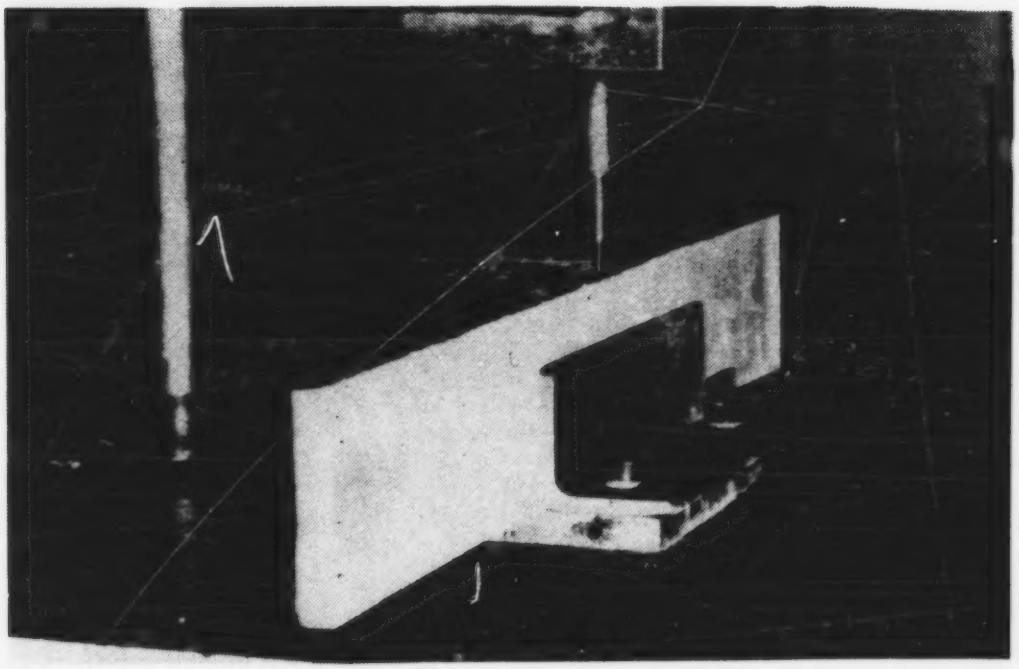

Figure 35- Core hardness test (before nail is inserted)

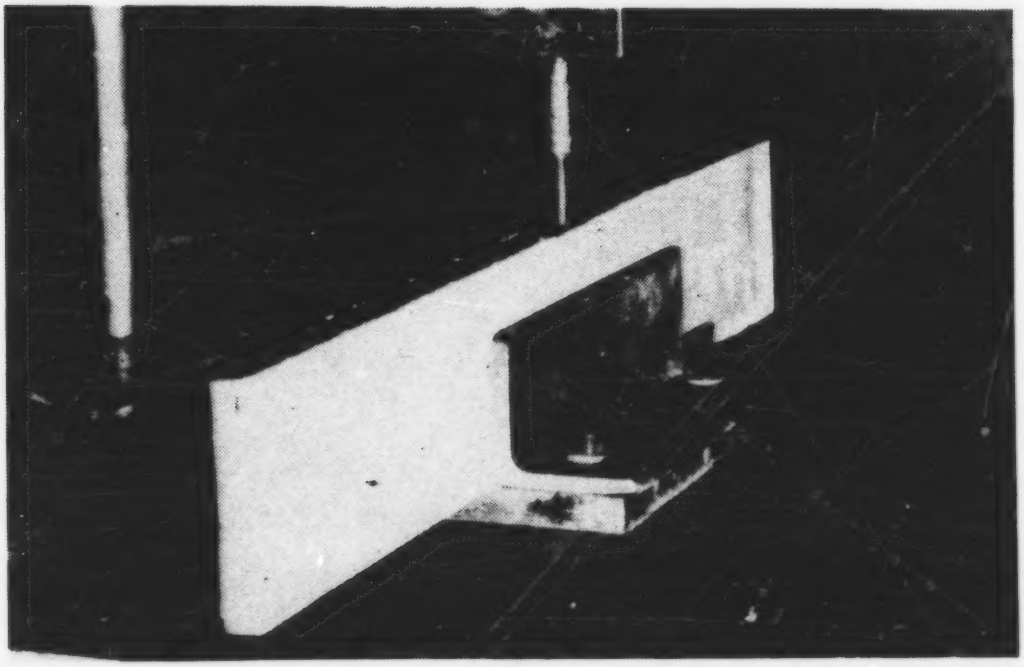

Figure 36- Core hardness test (after nail is inserted)

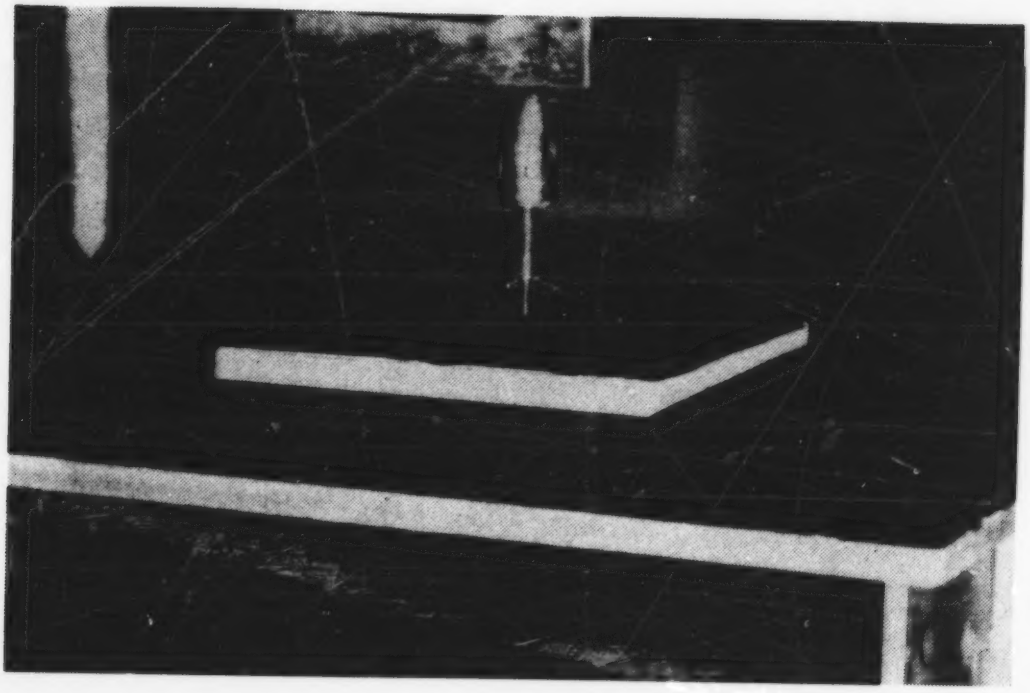

Figure 37- Nailhead pull resistance test (before nail is inserted)

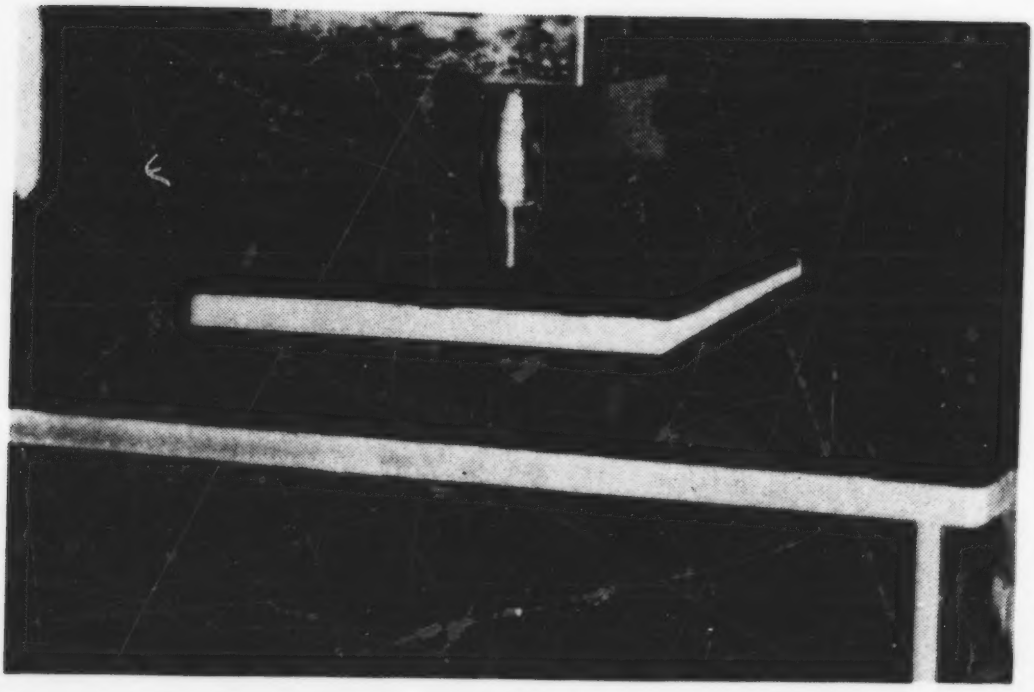

Figure 38- Nailhead pull resistance test (after nail is inserted)

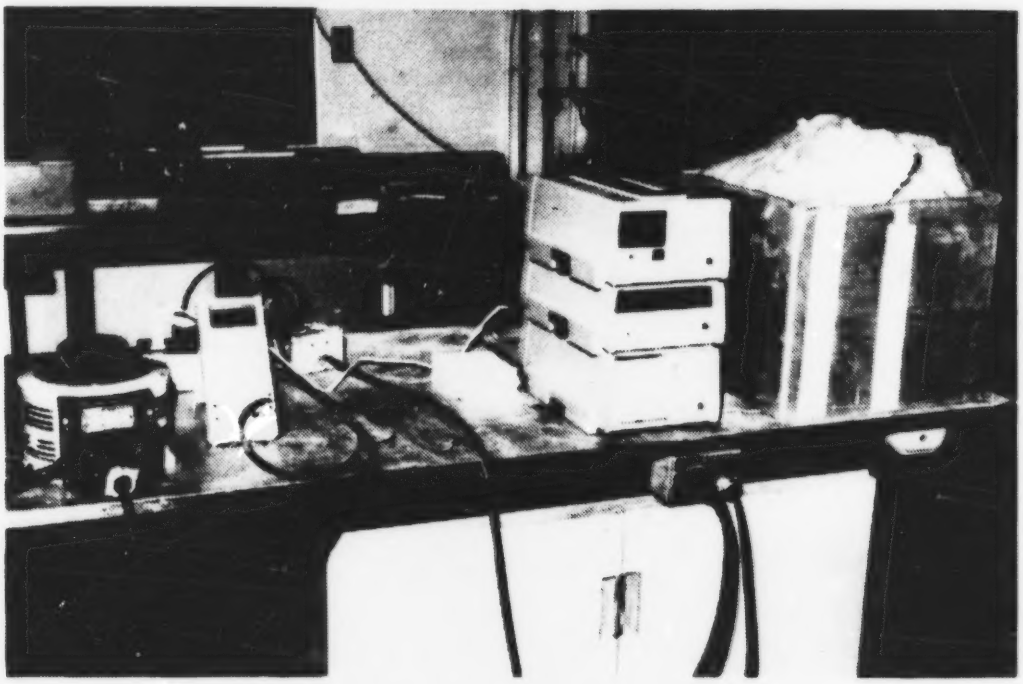

Figure 39- Thermal conductivity test

Table 29

MIX PROPORTION FOR 30% SUNDANCE FLY ASH REPLACEMENT
(water/stucco+ fly ash ratio = 0.58)

Gypsum hemihydrate (stucco) - 44.10%

Fly ash - 18.90%

Water - 36.53%

Starch - 0.28%

Paper - 0.16%

Foam - 0.03%

Table 30

BREAKING STRENGTHS OF WALLBOARD SPECIMENS WITH AND WITHOUT FLY ASH

SPECIMEN TYPE	PARALLEL GRAIN Failure load (N)				CROSS GRAIN Failure load (N)			
	1	2	3	Avg.	1	2	3	Avg.
Pure Gypsum	250	270	170	230	520	470	510	500
Wabamun	270	280	280	277	510	490	470	490
Forestberg	300	270	230	267	510	480	480	490
Sundance	260	240	280	260	640	620	740	667

Table 31

CORE HARDNESS OF WALLBOARD SPECIMENS
WITH AND WITHOUT FLY ASH

SPECIMEN TYPE	FORCE (N) 1	2	3	AVG.(N)
Pure Gypsum	110	100	100	104
Wabamun	370	300	400	357
Forestberg	410	370	410	397
Sundance	260	230	270	253

Table 32

NAILHEAD PULL RESISTANCE OF WALLBOARDS
WITH AND WITHOUT FLY ASH

SPECIMEN TYPE	FORCE (N)					AVG.(N)
	1	2	3	4	5	
Pure Gypsum	580	540	640	680	650	618
Wabamun	670	640	650	620	430	645
Forestberg	540	560	580	420	520	550
Sundance	540	620	580	680	560	596

Table 33

MASS PER UNIT AREA OF WALLBOARD SPECIMENS WITH AND WITHOUT FLY ASH

Specimen type	Average mass of 6 boards kg	Area of boards	Mass/unit area kg/m
Pure Gypsum	1.448	0.120	12.070
Sundance	1.322	0.120	11.020
Wabamun	1.363	0.120	11.360
Forestberg	1.316	0.120	10.970

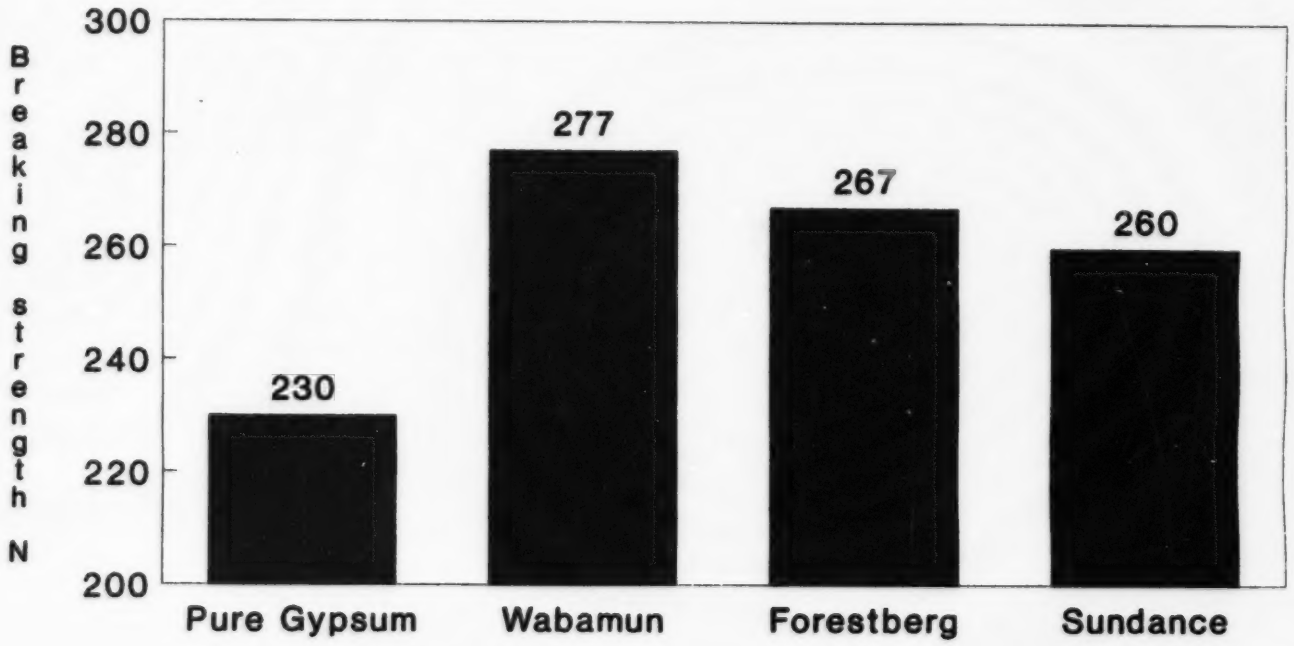

Figure 40: Breaking strengths of parallel grained wallboard specimens with and without fly ash.

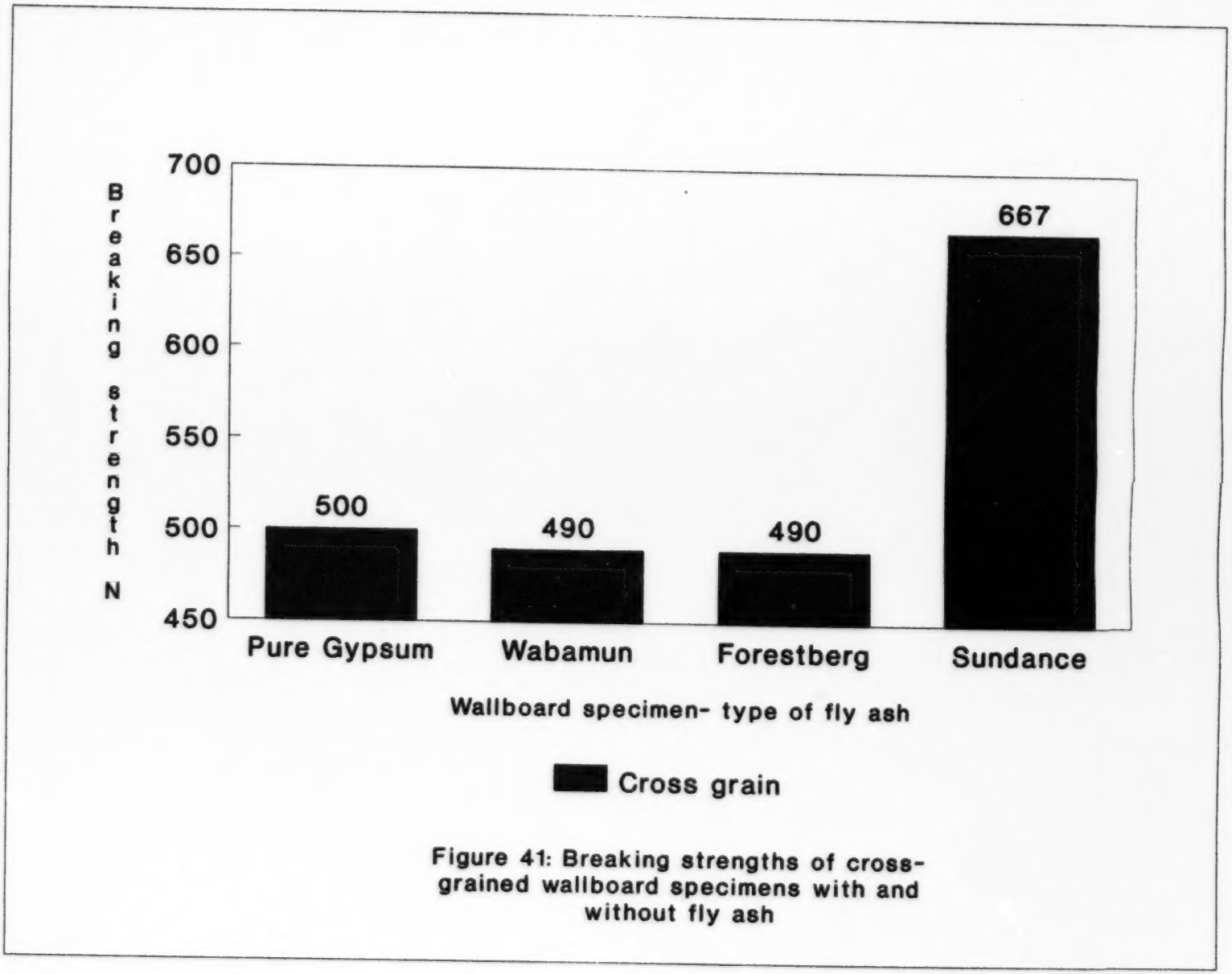

Figure 41: Breaking strengths of cross-grained wallboard specimens with and without fly ash

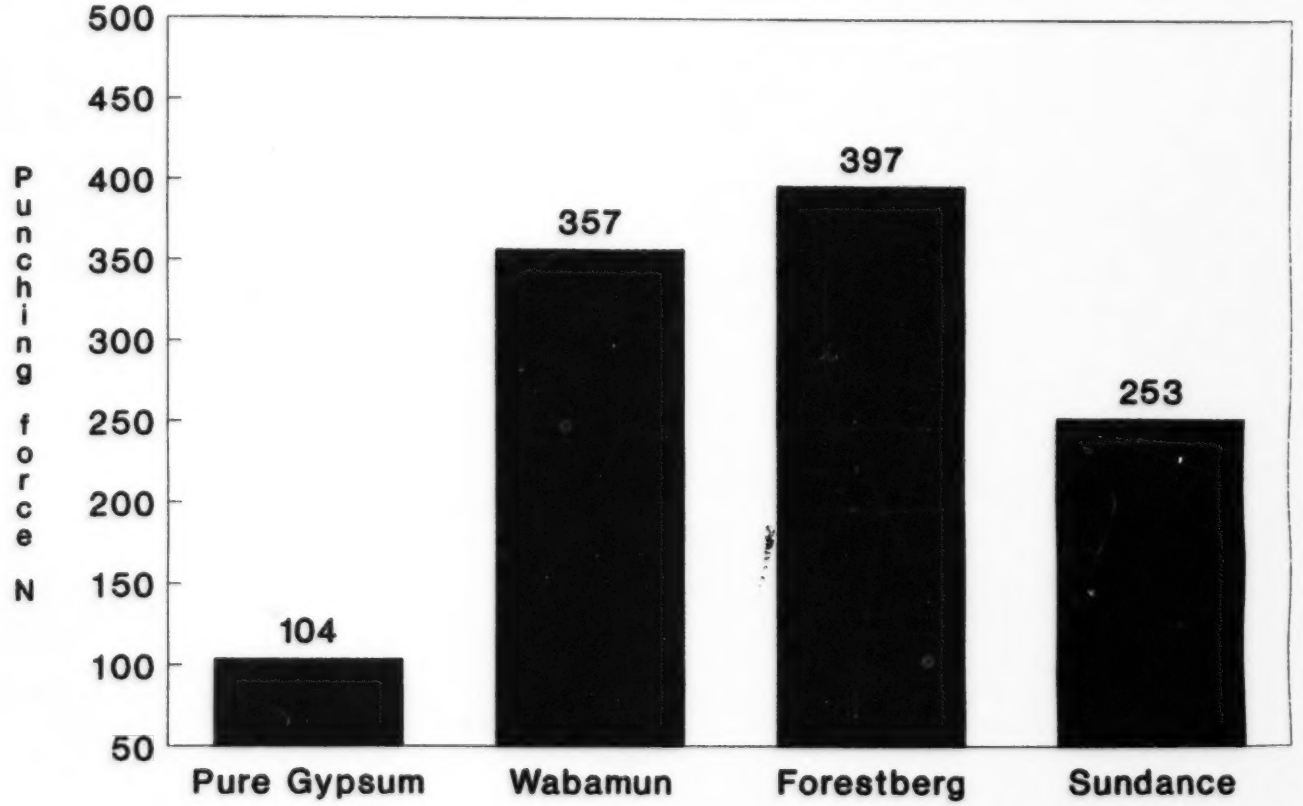

Figure 42: Core hardness of wallboard specimens with and without fly ash.

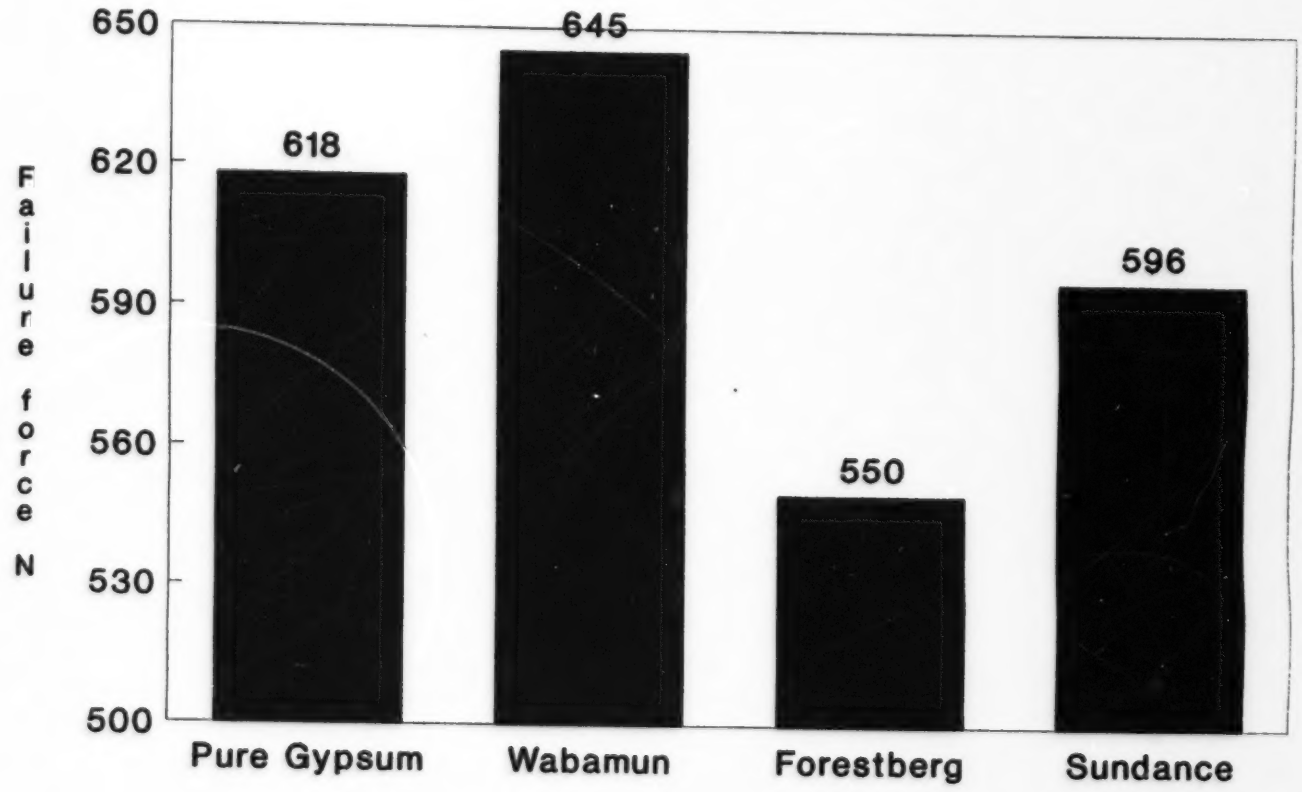

Figure 43: Nailhead pull resistance of wallboard specimens with and without fly ash.

Table 34

THERMAL CONDUCTIVITY OF WALLBOARD SPECIMENS WITH AND WITHOUT FLY ASH
SERIES I

Specimen Type	Temperature To	Temperature T1	Temperature T=T1-To (°C)	T Kelvin	Voltage (E) Volts	Resistance (R) ohms
Pure Gypsum	31.2	38.8	7.6	7.6	50.7	1440
Wabamum	30.7	38.8	8.1	8.1	50.7	1440
Forestberg	27.7	38.8	11.1	11.1	50.7	1440
Sundance	29.6	38.8	9.2	9.2	50.7	1440

Specimen Type	Power (Q) Q=E/R Watts	Area of Specimen(m^2)	Heat flux q=Q/Area W/m	Thickness L (m)	Thermal Cond. k=q*L/T W/mK
Pure Gypsum	1.785	0.012	75.640	0.013	0.1294
Wabamum	1.785	0.012	75.640	0.013	0.1214
Forestberg	1.785	0.012	75.640	0.013	0.0886
Sundance	1.785	0.012	75.640	0.013	0.1069

Table 35

THERMAL CONDUCTIVITY OF WALLBOARD SPECIMENS WITH AND WITHOUT FLY ASH
SERIES II

Specimen Type	Temperature To	T1	T=T1-To (°C)	T Kelvin	Voltage (E) Volts	Resistance (R) ohms
Pure Gypsum	31.2	36.7	5.6	5.6	42.7	1440
Wabamum	30.7	36.7	6.1	6.1	42.7	1440
Forestberg	27.7	36.7	6.7	6.7	42.7	1440
Sundance	29.6	36.7	6.9	6.9	42.7	1440

Specimen Type	Power (Q) Q=E/R Watts	Area of Specimen(m^2)	Heat flux q=Q/Area W/m	Thickness L (m)	Thermal Cond. k=q*L/T W/mK
Pure Gypsum	1.266	0.012	52.750	0.013	0.1225
Wabamum	1.266	0.012	52.750	0.013	0.1124
Forestberg	1.266	0.012	52.750	0.013	0.1024
Sundance	1.266	0.012	52.750	0.013	0.0994

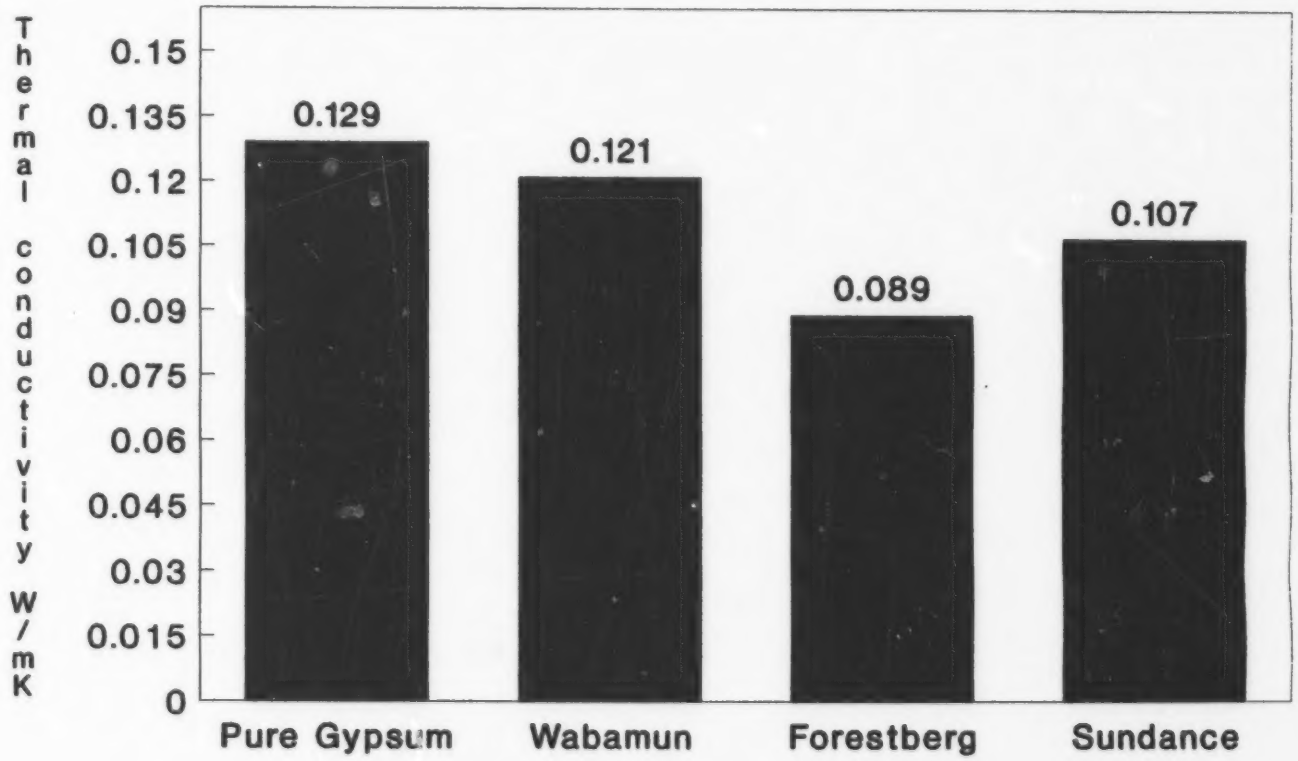

Figure 44: Thermal conductivity of wallboard specimens with and without flyash

Table 36

GAS FIRED KETTLE

OPERATING DATA

Period of test -	624 hours
Raw gypsum feed, total -	3048 tonnes
Plaster made, total -	2530 tonnes
Natural gas consumed per ton of feed -	772 cubic ft. = 21.861 m^3
Fuel value of natural gas =	3.05976 x 10^{10} J/m^3
Final calcining temperatures -	350°F
Average temperature of water removal -	260°F
Average temperature of stack gases at base of stack -	620°F
Average CO_2 in stack gases -	7.60%
Average gas temperature in firebox -	1980°F
Average temperature through ports -	1710°F
Average atmospheric temperature -	73°F
Average temperature of raw gypsum feed -	84°F
Average temperature of outside of kettle-setting brickwork -	152°F
Exposed area of external kettle-setting brickwork -	70.14m^2
Exposed area of top of kettle -	18.58 m^2